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A MONTHLY MAGAZINE FOR ENGINEERS

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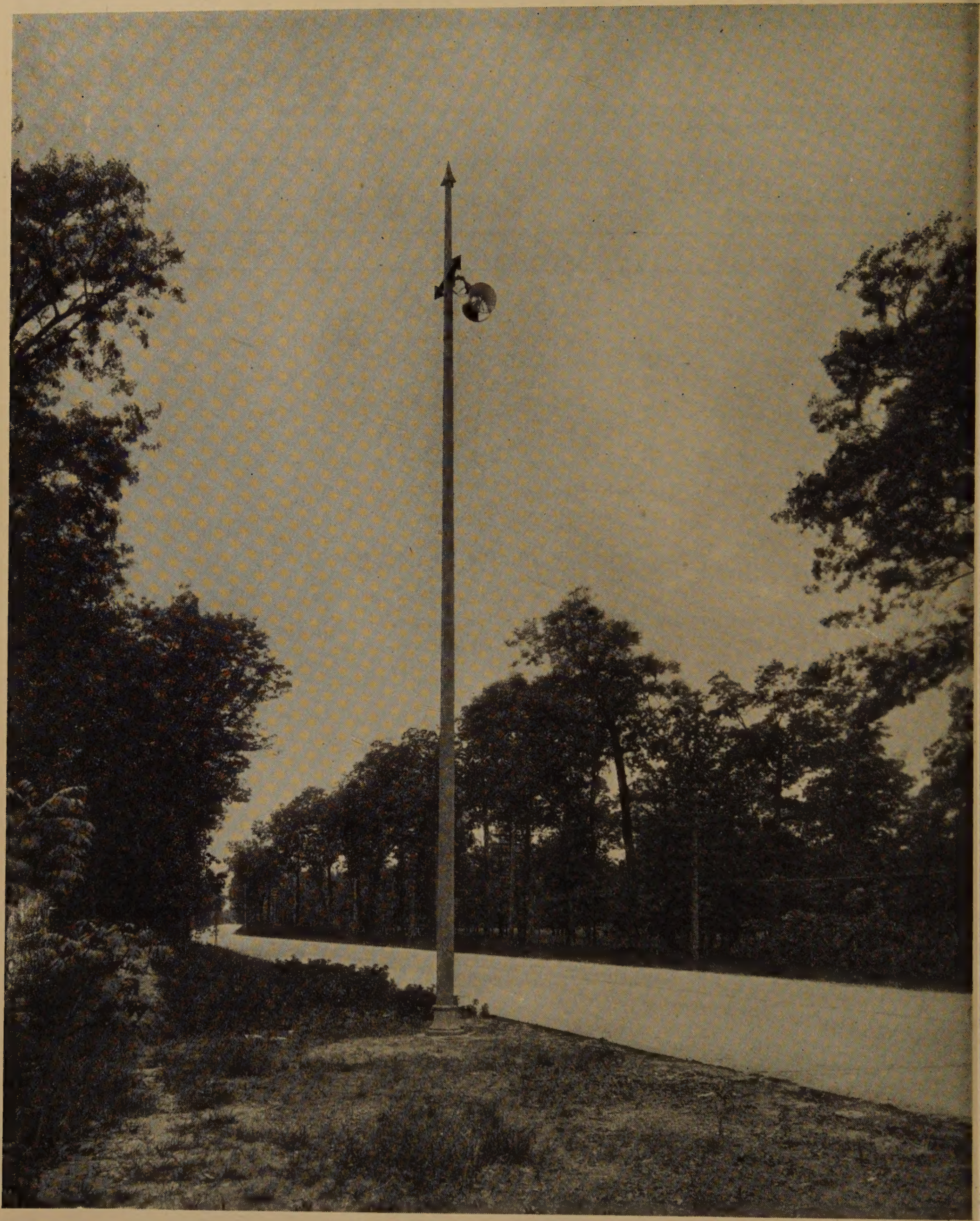

The Lincoln Highway is one of a series of magnificent national roads planned to cover the entire country. The lighting of these highways has received much attention from illuminating engineers and the lighting unit shown above on the Ideal Section of the Lincoln Highway gives results in keeping with the excellence of the roads themselves

GENERAL ELECTRIC REVIEW

SCIENTIFIC CRYSTAL GAZING

During the middle ages there arose a great discussion as to how many angels could dance on the point of a very fine needle without jostling each other. The debate was carried on by the best educated people of the day and lacked nothing in vigor, but the result brought about no improvement in the happiness or mode of living of the people of that time or since.

In after years, science has come into being and its devotees expend great energy in the consideration of an endless variety of subjects. To many of us laymen, some of these subjects may initially seem to have as little relation to our daily lives as does the matter of the angels and the needlepoint. For example, at the time the knowledge was gained, how many people regarded as of any great concern to them what made the leg of Galvani's frog twitch, or how fast a falling stone gains velocity, or why dust is able to remain suspended in air? Or today, how many of us realize that it is of great importance to know the shape and dimensions of an atom of copper or the stiffness of a molecule of linseed oil?

Compared to Galvani's time, there is this difference however in the formation of public opinion today. We are more ready to acknowledge as of value that work of the scientist of which we have but little understanding.

Yet why is it that we are justified in feeling that one group of men is performing a useful and lasting service when determining how many electrons gyrate about the intangible nucleus within an atom and another group of men accomplished nothing in an equally earnest endeavor to arrive at the number of intangible beings that could move about a needlepoint?

The reason is that the scientist limits his activity to those things which he can investigate by experiment and thus be guided by facts in his brain conjurings. Moreover, by relying on discovered facts, he is assured that his results are reproducible.

No scientific discovery is worthless. Though it may not be of service immediately, it will sooner or later find useful application.

Looking backward, for instance, the electrical industry is the outcome of the discovery of what made the leg of Galvani's frog twitch. Looking forward, the discovery of a method of determining precisely the structure of crystalline matter holds wonderful promise for mental and material development. Through its investigation by x-ray diffraction we are given an insight into the interior of things far beyond the power of the microscope, and thus we may hope to learn the fundamental reasons for many of the inherent characteristics of materials and how best to manipulate them.

The word "crystal" brings to mind for most of us a few scattered examples like sugar and table salt. But nearly everything solid with which we have to deal throughout our lives is composed of crystals. Natural silk is said to owe most of its desirable properties to the fact that it is made up of crystals. Wood and cotton are composed of cellulose, and cellulose is crystalline to some extent at least. Clays are composed of tiny crystals and a study of their types before and after the clay is fired in kilns is of great importance in the ceramic industry. All metals are made up of crystals and the whole art of the mechanical working of metals depends upon the size and orientation of these crystals and upon the space arrangement of the atoms which compose them. In fact it has been asserted by some that "the language of crystal structure will soon become the language of metallurgy and metallography."

Because crystallography, particularly by x-ray diffraction, has in the hands of the physicist and chemist already revealed its wonderful possibilities for industrial purposes, we have arranged with Dr. Davey to write for our columns a series of articles under the title of "Study of Crystal Structure and Its Applications." Though the earlier installments are necessarily rather abstract on account of the radical nature of the underlying principles, they are essential to a full understanding of the later installments describing the practical utility of this new tool now available to industry.

Operation of 1200-lb. Pressure Generating Unit at the Weymouth Power Station, Edison Electric Illuminating Co., Boston

By E. W. Norris
Stone & Webster, Incorporated

One solution to the insistent demand for better and better economy of power production lies in raising pressures and temperatures, thereby making available wider ranges of temperature over which to work the steam. The building of steam turbines suitable for such operation presents no insurmountable obstacle for this type of prime mover is capable of utilizing as high steam pressures and temperatures as can be generated. Great engineering interest is therefore attached to the 1200-lb. turbine-generator, of approximately 3000-kv-a., described in the following article, for it will be the first of so high a pressure to be placed in commercial service in this country. Its unique thermodynamic features are outlined and its operation under both normal and emergency conditions is explained.—Editor.

Apparatus

The high-pressure installation at the Weymouth Power Station will consist of a boiler and turbine designed to operate at a maximum steam pressure of 1200 lb. per sq. in. After generating the steam at this pressure, the boiler will superheat it to 700 deg. F. total temperature and then deliver it to the turbine. From the turbine the exhaust at 360 lb. pressure will return to the boiler where its temperature will again be raised to 700 deg. F. The steam will then be delivered to the main steam header for use in the normal-pressure (350-lb.) turbine-generators. The high-pressure boiler and high-pressure turbine are to be operated together as a unit, giving complete certainty as to steam path and division of load.

The 1200-lb. steam boiler is a modification of the conventional cross-drum type, the heating surface consisting of 2-in. dia. tubes 15 ft. long, arranged in three passes. The tubes are separated into upper and lower banks, with a primary superheater between. Above the upper bank is a secondary superheater or reheater. The tubes of this reheater are at right angles to the tubes in the main heating surface and are so arranged that the gases pass through them between the first and second passes of the boiler. The main boiler baffle between these passes is extended up into the reheater, by means of an adjustable damper. When this damper is in its lowest position, all the gases are forced to pass through the reheater. When the damper is raised to its highest position, the reheater is by-passed and is practically out of service. Intermediate positions of the damper give varying degrees of effectiveness to the reheater.

The boiler is fired by the conventional type of Taylor stoker.

A special arrangement of safety valves is used to protect the boiler. The cross-drum is provided with a series of such valves, set to blow at 1200 lb. pressure. In order to protect the primary superheater, a safety valve is placed on its outlet and set to blow at 1190 lb. It is possible that after operating the seats of these valves would be destroyed, which would render necessary the shutting down of the boiler and the reseating of the valves before continuing operation. In order to avoid such undesirable wear of the valve seats, a warning to the fireman is provided in the form of two telltale valves. These are placed on the discharge from the primary superheater, are of small diameter and are set to blow at 1170 lb. per sq. in. Between them and the steam connection are placed gate valves. In operation, one of these gate valves will be closed; the other open. Should the pressure rise near the 1200-lb. point, the first telltale valve will blow, giving the fireman an opportunity to reduce the pressure on the boiler in time to prevent the main valves from blowing. The telltale valve which has blown can be shut off by the gate valve below it, and the other telltale valve put into service by opening its gate valve. The first telltale valve can then be removed and reseated if necessary. In this way the boiler can be kept in continuous operation even though the safety valves should require special care.

The control for the high-pressure boiler is of the Bailey electric relay type, and is similar in all respects to the control supplied to the normal-pressure boilers at the Weymouth station. In operation, the 1200-lb. boiler will not be regulated by the master pressure controller of the normal-pressure boilers but will be operated by push buttons on its own control board.

The 1200-lb. turbine-generator is of the straight impulse type. The initial steam pressure is to be variable, with a maximum value of 1200 lb. per sq. in. at 700 deg. F. total temperature. The exhaust pressure is to be constant at 360 lb. per sq. in., variable temperature.

The turbine casing is provided with shaft packing glands at both high-pressure and exhaust ends.

The turbine governor is of the conventional type, but designed so that the synchronizing spring has sufficient range to place the governor completely out of action when desired during normal operation of the unit. The turbine throttle is supplied with an oil-operated trip mechanism.

The piping for the installation is to be of very simple design. It will consist of a single high-pressure line connecting the primary superheater outlet nozzle on the boiler to the turbine throttle, an exhaust line connecting the turbine exhaust to the reheater inlet on the boiler, and a third line connecting the reheater discharge on the boiler to the main steam header. Between the high-pressure steam line and the exhaust line there will be a by-pass supplied with a desuperheater. In general, the steam will flow from the boiler drum through the primary superheater to the high-pressure piping. At the outlet of the primary superheater there will be placed a motor-operated gate valve for use as a stop valve in normal and emergency service. No stop check valve is to be used at this point as no other boilers will be connected into the line. After flowing through the turbine, the steam will be returned to the reheater in the boiler, and, after passing through the reheater, will flow to the main steam header. A stop check valve will be provided on the outlet of the reheater in order to prevent steam from the main header flowing back into the reheater. A simple check valve in the exhaust line between the turbine and the reheater will prevent steam, discharged through the by-pass, from flowing back through the exhaust connection into the turbine. A conventional stop valve will be provided where the steam enters the main header.

In the by-pass, a special type of trip valve will be installed. This valve is similar in design to the turbine throttle, and is equipped with an oil-operated trip gear, but this trip is designed so that the valve will open instead of closing when actuated. This trip gear will be placed in parallel with that on the turbine throttle, the purpose being to by-pass the steam immediately should the turbine throttle be closed by the overspeed device. Beyond the by-pass valve will be inserted a nozzle for throttling the 1200-lb. steam and expanding it to 360 lb. pressure before it enters the exhaust line and is returned to the boiler reheater. Beyond this nozzle there is to be a series of water jets for desuperheating the steam. These jets will receive water from the 425-lb. pressure boiler feed line, through a small trip-opening valve operated by the trip on the by-pass valve. Both the by-pass valve and the desuperheating water supply valve can be manually operated at any time.

In order to remove condensation from the high-pressure steam line before normal operation has been established, a drip pocket will be provided and connected through a special throttling valve to the 360-lb. exhaust line. By this means, the line may be blown clear at any time and the water discharged into the 360-lb. system where the normal pressure traps can remove it.

Starting Up

In starting up the plant, the boiler stop valve may be opened before raising steam on the boiler as there will be no other boilers on the line. The stop valve at the main steam header, and the stop check valve on the discharge side of the reheater, may also be opened. The high-pressure steam line may be kept clear of water by using the blow-off from the high-pressure drip pocket to the turbine exhaust line. The reheater damper should be raised so as to by-pass the reheater. Steam should then be raised in the usual way. The by-pass valve near the turbine should be opened as steam is raised, so as to provide a circulation of steam as soon as the pressure in the boiler exceeds that in the main steam header. In circulating steam, the superheat of the steam returned to the reheater can be regulated by means of the water supplied to the by-pass desuperheater.

The feed pump for the high-pressure boiler is of the motor-driven centrifugal type, controlled by an excess-pressure-type regulator that gives a combination of hand and automatic regulation. As the boiler pressure rises the hand controller should be thrown over gradually from point to point, so that the automatic regulator will cover the range of the actual demands on the pump.

The turbine may be warmed up by gradually opening the throttle in the usual way, the turbine and by-pass valve operating in parallel at this time. The advantage of using the by-pass is that the increasing load on the boiler will be made more uniform and the effect of any sudden change in demand for steam by the turbine will be minimized. This added protection is desirable for a boiler operating at high pressures where the latent heat of the steam is low in comparison to its total heat.

The leak-off steam from the shaft glands of the turbine will be piped to a surface condenser and feed-water heater. As the high-pressure turbine is to be operated in conjunction with one of the main 350-lb. pressure turbine-generators, before starting the high-pressure unit, the valves between the gland leak-off points of this unit and the gland steam condenser and the twelfth-stage extraction heater of the corresponding main unit should be opened. Should an emergency arise, a water-jet condenser provided for condensing the steam from the glands will take care of the steam in case the condenser and heater should be temporarily out of service.

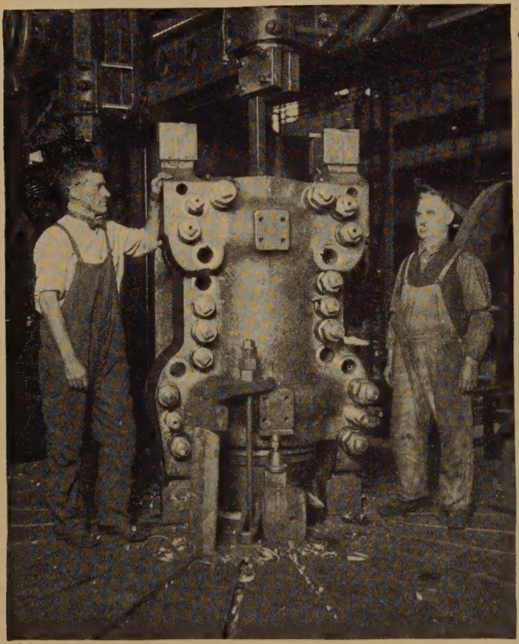

Fig. 1. Top View of the Wheel Casing of the 1200-lb. Pressure Curtis Steam Turbine

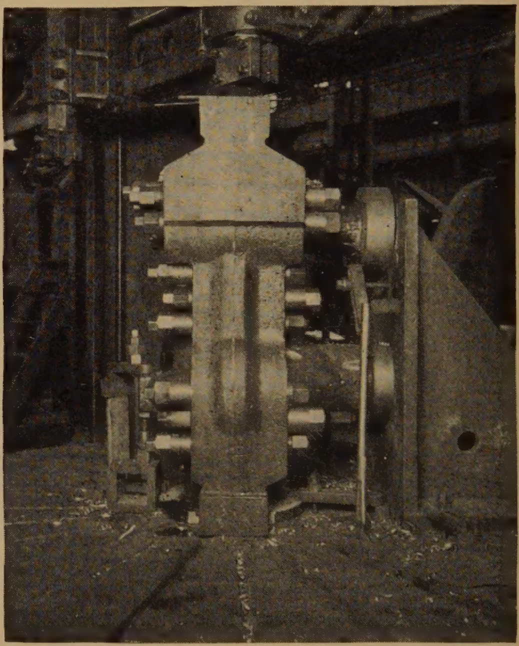

Fig. 2. Side View of the Casing Shown in Fig. 1

After the turbine has been warmed up, it may be brought up to speed and placed under the control of the governor, the throttle valve being opened wide. At this time the boiler will be operating at reduced pressure, say between 600 and 800 lb. per sq. in. and at low capacity. Steam will then be flowing to the turbine under the control of the turbine governor and the excess by-passed through the by-pass valve to the turbine exhaust and passed through the reheater to the main steam header.

The turbine-generator may be synchronized and placed on the line in the usual way except that as soon as the generator circuit breaker is closed, the turbine governor should be placed out of operation by tightening the synchronizing spring sufficiently to bring the range of the governor above the synchronous speed of the machine. As soon as this has been done, the turbine will be carrying a load equivalent to the steam flowing through it. The by-pass valve should now be closed and the boiler brought up to its operating pressure.

Normal Operation

During normal operation, the turbine will develop power in accordance with the steam passing through it. It will operate at synchronous speed in parallel with the main bus and its output be governed entirely by the steam pressure.

The flow of steam will be proportional roughly to the pressure, so that the output of the boiler and the turbine-generator can be regulated by varying the pressure on the boiler. For base-load operation, the boiler pressure should be maintained constant.

The control of the boiler will be by push buttons from its control board. The Bailey combustion control will, in general, maintain the proper relations of air and coal feed to the boiler and, under uniform conditions, will maintain a constant pressure. The fireman will be called upon to take care of variations due to inequality of coal, clinkering, etc. This can be cared for in the usual way through manual control of combustion.

The temperature of the steam returned to the main header can be regulated by the reheater damper. This damper will be operated through motors controlled by push buttons placed on the boiler control board.

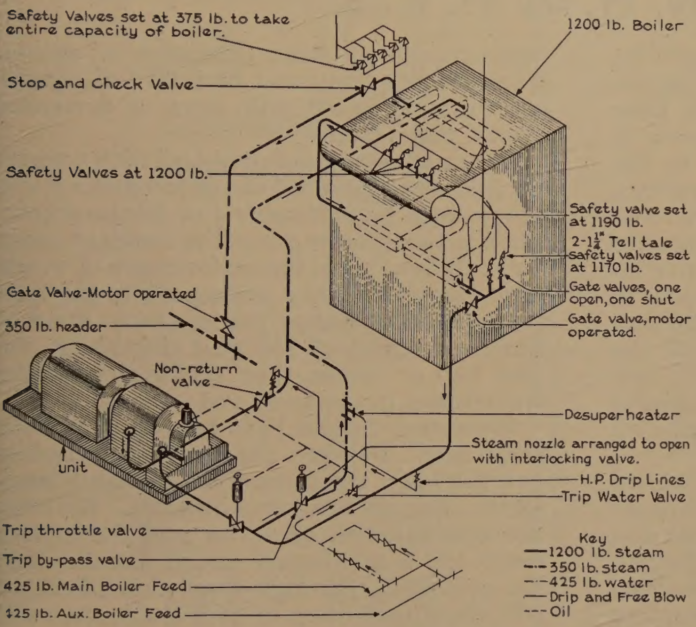

Fig. 3. Diagram of the Piping Systems for the 1200-lb. Boiler and Turbine-generator Power Plant Unit

The boiler feed will, in general, be from the motor-driven pump under automatic regulation. No automatic waterline control is provided. The boiler feed should be regulated by hand at all times.

To reduce wear on the blow-off valves it is proposed to blow down the boiler under reduced pressures of 600 or 800 lb. The safety valves are provided with lifting gear and they can conveniently be tested at the same time.

Shutting Down

In general, the process of shutting down the plant will be exactly the reverse of starting up. The boiler pressure should be reduced, attention being given to the reheater damper and the boiler feed pump, to maintain correct reheating temperatures and proper feed pressures. When the boiler pressure has been reduced to the desired point, the by-pass valve may be gradually opened, relieving the turbine from load. The exhaust steam temperature can be regulated by admitting more or less water to the by-pass desuperheater.

The turbine may now be relieved of load from the main switchboard, by means of the synchronizing device on its governor, and the generator taken off the line. The turbine throttle should, of course, be closed and the boiler taken off the line in the usual way. The piping system can be shut down by closing the stop valve in the 1200-lb. line at the boiler, and closing the stop and check valves and the stop valve in the normal pressure line to the main header.

Emergency Stopping

A special condition arises when an emergency requires the immediate shutting down of the turbine. When the overspeed or oil-pressure trip of the turbine operates and closes the throttle valve, the by-pass valve is to be opened at the same instant. This valve will allow the steam to flow through an expanding nozzle having the same capacity for flow as the turbine itself, and will discharge the steam into the turbine exhaust through a desuperheating spray. When the by-pass valve trips open, it will also open a water valve to supply water from the 425-lb. boiler feed system to the desuperheater spray nozzles. The effect of this by-pass is to reduce the high-pressure steam to 360-lb. pressure and remove its superheat. It will then be passed through the reheater in the boiler in the usual way and be delivered to the main header. Thus the boiler will not be immediately affected by the instantaneous shutting down of the turbine as the by-pass will permit the delivery of the full capacity of the boiler without interfering with any of its functions. The reheater will be protected as the steam discharged from the by-pass will pass through it at approximately normal temperature, due to the desuperheating. In addition, there will be no tendency for the high-pressure safety valves to blow off, thus relieving them from unnecessary wear.

The 350-lb. steam system will be fully protected by the safety valves mounted on the discharge of the reheater. These valves are sufficient to discharge the full capacity of the high-pressure boiler should the pressure tend to rise in the 350-lb. system.

After such a shut-down, the turbine may be restarted by opening its throttle and gradually closing the by-pass, or the boiler can be shut down and taken off the line at the convenience of the operating force. In either case, the routine will be approximately the same as in normal starting or shutting down.

New Type of Single-phase Locomotives for the N. Y., N. H. & H. R. R.

Unusual interest is being displayed by railway engineers in the new type of single-phase locomotives which have just been ordered by the New York, New Haven & Hartford R. R. Co., to be built jointly by the General Electric Company and the American Locomotive Co. Two of these units are to be used for switching in general yard service and the other five are for freight service on the main line between the Oak Point yards in the Bronx and New Haven. Outline drawings of them are shown in Figs. 1 and 2 on the opposite page. The contract for the new locomotives calls for operating characteristics suitable for functioning in multiple unit with the present single-phase locomotives.

The New York, New Haven & Hartford Railroad Co. was the first main line railroad to adopt the single-phase system and has now in operation 115 locomotives handling freight, passenger, and switching service. The road also operates 35 single-phase motor cars, four of which were equipped by the General Electric Company. A number of years ago the General Electric Company conducted exhaustive tests on equipment for a motor-generator type of locomotive and prior to that time in 1908 furnished a box type locomotive to Paul Smith's Electric Light & Railroad Co. which operated on the same principle. This locomotive is still in daily operation.

The new locomotives under construction for the New York, New Haven & Hartford R. R. will take 11,000-volt power from the single-phase trolley, step it down to 2300 volts, and then convert it through a synchronous motor-generator set to direct current for driving standard series railway motors. Each locomotive in effect contains a traveling substation which permits it to take advantage of both high-tension alternating-current distribution, and direct-current traction motors, which are admittedly most satisfactory for traction purposes. The direct-current motors together with the motor-generator set permit a greater simplicity and flexibility of control and it is expected will show a favorable overall maintenance.

The main generator is designed with a variable field and the speed of the locomotive will be regulated by field control of this generator. The traction motors are of the standard series direct-current type, the performance of which is well known. They are geared to the axle through cushion-type gears which allow a small movement of the gear ring about the gear hub or center, thus minimizing shocks and stresses in the gears and pinions.

Protective devices have been studied with great care. Between the pantograph trolley and the main transformer a time-limit automatic oil circuit breaker is installed. Between the direct-current generator and the motors there are a high-speed circuit breaker and line switches. The high-speed circuit breaker will afford protection to both the motors and the generators and will ordinarily prevent the opening of the time-limit switch or of the trolley or feeder sectionalizing switches and will thus prevent any interference with the continuous operation of the motor-generator set.

The system of control, by varying the field strength of the generator, in connection with the characteristics of the motor-generator set, gives a locomotive which is extremely flexible and adaptable to all operating conditions. It also has the very desirable characteristic of operating at a power-factor of unity or better under all ranges of load. The set has been made of sufficient capacity to take care of the rated loads and will also furnish an appreciable amount of wattless current, especially at light loads for power-factor correction. This tends to improve the trolley voltage for all load conditions and should be of material benefit in the operation of the entire system.

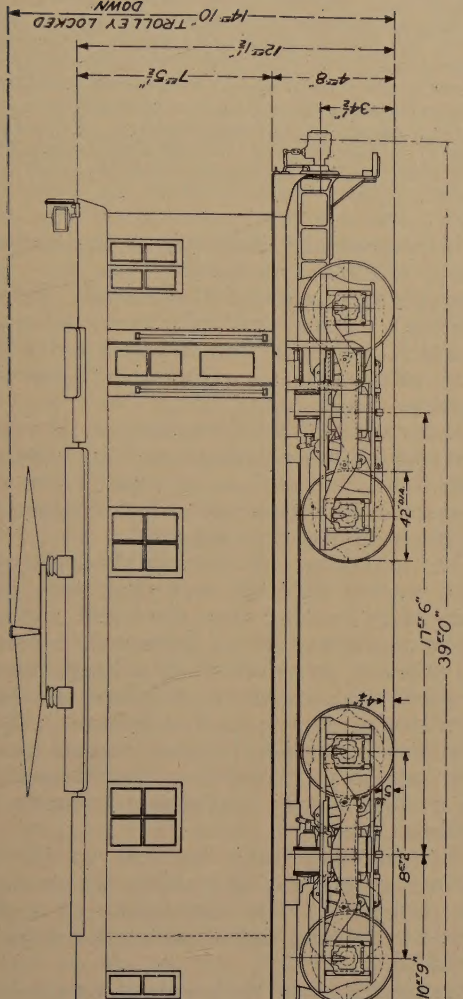

Fig. 1. Preliminary Outline of One of the New A-c.-D-c. Switching Locomotives for the New York, New Haven & Hartford Railroad

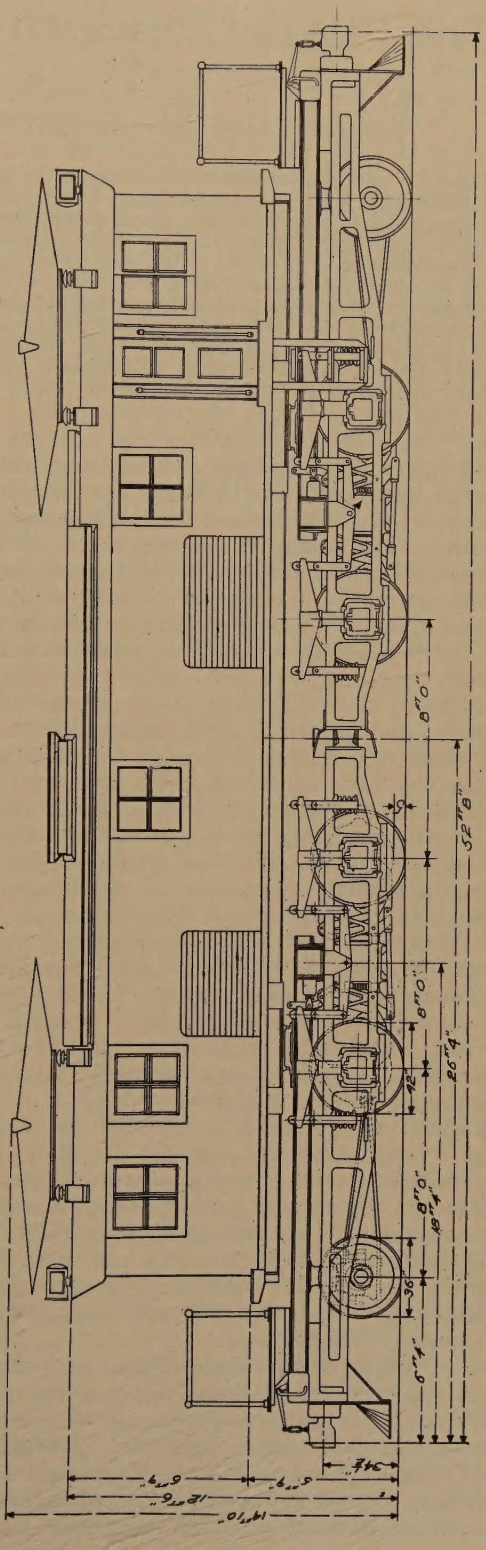

Fig. 2. Preliminary Outline of One of the New A-c.-D-c. Freight Locomotives for the New York, New Haven & Hartford Railroad

The Field of Research in Industrial Institutions

By E. W. Rice, Jr.

Honorary Chairman of the Board of Directors, General Electric Company

Research into the properties of materials, the laws of Nature, and the interaction of these two is always worth while. Even in the case of failure to reach a desired goal there is usually a resulting by-product of new knowledge which is sometimes of a quite unexpected variety. Often this may be turned to immediate use in some other branches of work, and then again there may appear to be no useful application for it. However, all such information is of potential value, and no thoughtful person would be so rash as to predict that any of it will forever remain of no practical worth. Research in the realms of pure science and in the current problems of production has given birth to new branches of industry, has fairly revolutionized production methods in existing industries to their great advantage, and is fundamentally perfecting the products of manufacture. A consideration of the field for this work, particularly in the electrical industry, is presented in the following article which was delivered, September 18, 1924, as a paper by the author at the Franklin Institute on the occasion of the Centenary Celebration of its Founding.—Editor.

At this Centenary Celebration of the Founding of the Franklin Institute, our thoughts naturally turn to Benjamin Franklin, that remarkable man—sage, philosopher, statesman, and scientist—whose name this Institution has borne for a hundred years, an Institution which during the century of its existence has performed a service that has shed luster upon the illustrious name which it bears.

Franklin's research into the nature of lightning, and its identification as electricity, by drawing the lightning from the clouds in the famous kite experiment, was not only remarkable for the time in which he lived, but would probably rank with the best methods of modern scientific research, as a model of simplicity of apparatus, and equally convincing in its solution of the problem.

The lightning rod which he invented for the protection of buildings and similar structures was perhaps the first illustration of the practical value of scientific research, and may, without too great a stretch of imagination, be considered as marking the beginning of our electrical industry.

Franklin was elected a member of the Royal Society of London without his solicitation, and was excused from payment of dues. He was, so far as the author is aware, the first American to receive this great honor. While the Royal Society honored itself in thus honoring the great Franklin, he himself greatly appreciated the gift, and especially the manner of its bestowal.

We all think of the Royal Society as the Mother of Research, and the vision of Davy, Faraday, and Dewar, to speak only of a few of those who have gone, immediately arises in our minds. If we wish to be instructed as to the best methods of conducting research or of recording its results for the benefit of the world, we turn instinctively to the inspiring records of Faraday's work.

Davy's discovery of the electric arc and Faraday's discovery of electro-magnetic induction were the foundation upon which, years afterward, was built our electrical industry.

Dewar's scientific research into low temperatures led to his invention of the "thermos bottle" which has become one of the conveniences and necessities of our modern life, and the basis of a large industry.

The activities of industrial institutions range over a field so vast that only those concerning mainly the electrical industry will be considered here. Even such a restriction will not prove much of a limitation for the electrical industry touches all other industries in every phase of human activity: agriculture, mining, forestry, water power, steam power, transportation, communication, and in fact nearly everything in-doors and out-doors.

The difficulty may be due to the all-embracing nature of electricity, which we are now taught is the substance or entity, atomic in nature, out of which all matter is produced.

Nowadays when we speak of research, we usually have in mind scientific research. Industrial research may not only partake of the nature of pure scientific research, but, reaching into a broader field, interests itself in the applications of science to lighting, power, chemistry, physics, medicine, mechanics, education, and sociology; every phase, in fact, of human endeavor.

At the same time, it is not easy to define "industrial research" satisfactorily, as the same event or process may be looked upon as research by one, development by another, and mere improvement by still another.

We experience a similar difficulty in attempting to define "field of research," as industry itself is constantly changing, forever expanding, the field of research of today becoming the field of technical development on the morrow, and that of commercial application the day after tomorrow.

C. F. Kettering, President of the General Motors Research Corporation, has attempted to define the "field of research" by a process of exclusion, saying in effect: "If you have no problems in your business, if you are perfectly satisfied with your product, your processes, and your costs in all respects, if you have no troubles from competition or other sources of worry, and are sure you are not going to have any for ten years to come, then you *may* not need research." It is obvious that Mr. Kettering used the word "may" quite advisedly.

What business is free from problems and troubles and worry, even for a day?

There was a time, about 1911, when one might have thought that the incandescent lamp business in America would fairly meet Mr. Kettering's specifications. We were very happy and proud of our latest vacuum lamp, with its filament of tungsten wire, an original and remarkable product of our research laboratory. Why should we worry, why not rest in "comfortable complacency" after our strenuous labors? But our restless researchers decided otherwise. Even then they were discovering new laws governing the conduction of heat from wires to surrounding gases, a research which resulted eventually in a still more efficient product, the gas-filled lamp.

I remember, about the year 1900, having a conversation with several eminent scientists in which the discussion turned to the peculiar position of carbon in the electrical art. Carbon had been found to be the only substance which could be used for the electrode in the arc lamp, for the filament in the incandescent lamp, and for the brushes for commutation in direct-current dynamos. It was agreed that probably nothing else would ever be found to take the place of carbon for such purposes. It seemed as though this material had been created especially for use in the electrical art, along with copper for conductors and iron for magnetic purposes. We felt secure in our opinion, as all the years of the industry had disclosed no substitute.

In less than ten years a great revolution took place, and tungsten displaced carbon in the incandescent lamp, and magnetite electrodes were found to give very superior results in certain arc lamps.

I recently re-read an address given 25 years ago by that master of industrial research, Professor Elihu Thomson, on the subject: "The Field of Experimental Research."[1] While the entire address is worth reading, even at the present time, quotation will be made of only a few paragraphs that seem especially pertinent.

Speaking of experimental research, which is one phase of industrial research, he says: "Whatever may be our ideas of fundamental entities, as expressed in various theories, whether, as an example, we regard the ether as like an infinitely mobile fluid, or as an incompressible solid, or as a jelly, or whether we are inclined to think that, being an electro-magnetic medium, it may be without mechanical properties, which properties depend in some way upon the electro-magnetic nature of the ether, we cannot reach sure ground without the experimental test."

He emphasized the interdependence of scientific and industrial research, saying of the industrial researcher: "He must learn to render available to science the resources of the larger workshops and industrial establishments. The application of physical principles upon a large scale in such works has frequently in recent years resulted in great gains to science itself. The resources of the physical laboratory are often relatively small and meager compared with those of the factory. Experimental work in certain lines is now frequently carried on upon a scale so great and under such varied conditions as would be almost impossible outside of a large works. In no field has this been more true than in that of electricity during the past few years."

Professor Thomson gave this address in 1899. Many persons will easily remember the remarkable development in electro-chemistry which took place during the decade which was then just ending, starting with the development by Hall of the process of making aluminum in 1890, followed by the discovery of carborundum by Acheson in 1891, of calcium carbide by Wilson in 1892—all the result of scientific research, and each in turn the foundation of extensive new industries, the creators of new and untold wealth.

Then in 1894 came the discovery of the mysterious x-rays by Roentgen. We had scarcely time to become accustomed to this great marvel when Becquerel in 1896 announced his discovery of somewhat similar rays continuously shooting out from the metal uranium. Two years afterward the Curés made the great discovery of radium, and its even more powerful radiations.

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[1] "The Field of Experimental Research," by Elihu Thomson, American Association for the Advancement of Science, Aug. 21, 1899.

Sir Ernest Rutherford says: "Even the most imaginative of our scientific men could never have dreamed at that time of the extension of our knowledge of the structure of matter that was to develop from these two fundamental discoveries."

This same decade witnessed Marconi's feat of sending a message by wireless across the English Channel, the technical and commercial development of the electric trolley, the general introduction of alternating-current generation and transmission of electric energy, the harnessing of Niagara, and countless other achievements too numerous even to mention.

If an examination were made of the history of these developments, it would be found that they all owed their origins to scientific research.

Remarkable as is the preceding incomplete list of notable advances in the brief period of less than ten years, it will be remembered that almost any decade during the past 50 years may be credited with an equally wonderful record in the electrical field alone, beginning with the telephone of Bell and the incandescent lamp of Edison in the seventies, to the latest radiant children—wireless telegraphy and telephony, and radio broadcasting.

When it is realized that all this marvelous progress is founded upon the "experimental method" or, as we now call it, the "research method" of interrogating and attacking Nature and forcing her to yield her secrets for our benefit, is it any wonder that men have been impressed by the value of the scientific method, and that research work and research laboratories have increased so rapidly during the past few decades?

"Research" in the dictionary is defined as a "Systematic investigation of some phenomenon or series of phenomena by the experimental method to discover facts or to coordinate them as laws." L. A. Hawkins qualifies this definition by the statement that he would "limit the facts sought by research to generic facts," and points out that "it may be desirable to know the open-circuit voltage of a certain battery to another decimal point, but to obtain that fact by refinements of measurement is not research. It does not give us the kind of new knowledge or new principle which makes possible the development of new devices. Again, an industry may need a developmental laboratory to improve its apparatus, to develop new devices, and to find new applications for its products, yet none of it may be research. All these things have to do with specific things; they represent applied science or engineering. Research, on the contrary, has to do with generic facts or principles. It need have no connection with industry. It is fundamentally the same whether conducted at a university or in an industrial laboratory. It is essentially pure science until engineering development steps in to apply it."[2]

It is evident that in the foregoing comments Hawkins is speaking of research in pure science, and that for industrial research we require a broader definition. Perhaps we may define "industrial research" as a systematic search for information useful to the industry. It is obvious that the more we learn about our business, the better; that we may then direct its expansion more wisely, increase its usefulness, and insure its relative permanence.

To quote Rutherford again, he says: "In this age no one can draw any sharp line of distinction between the importance of so-called pure and applied research. Both are equally essential to progress."

In this country, up to comparatively recent years, in industrial circles, the word "laboratory" was commonly used to designate chemical laboratories. These were usually small and principally engaged in testing raw materials, and were not in any sense research laboratories.

There were in existence, in addition to such chemical laboratories, testing departments for the testing of materials purchased, and experimental departments generally confined to one or two rooms, called "model rooms" or "experimental rooms," in which new inventions and improvements relating to the industry were developed.

In the electrical industry the realization of the value of scientific methods was perhaps greater than in the older, well-established industries. There was a closer connection between the universities and technical schools and the electrical industry in its earliest days. The newness, combined with the highly technical nature of the electrical business, led those in charge of the engineering work to draw upon the colleges and universities for graduates trained in such scientific and technical knowledge as then existed. These men were set at work in the engineering and testing departments, and those of special aptitude were given opportunities in experimental departments to assist in the research and development necessary to a new industry.

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[2] "Research," by L. A. Hawkins, Canadian Electrical Association, June 22, 1923.

As is well known, the field covered by the electrical manufacturing industry includes nearly every article of an electrical nature; and of course such a variety of articles calls for the use of about every known material, the utilization of about every known physical, chemical, and mechanical process, and the application of a great number of human activities as well. Naturally, every article and all the materials and processes are subject to improvement, and therefore theoretically form a legitimate subject for industrial research.

In order to provide for the development of its apparatus and improvement of its processes, it has been found desirable, especially by the larger industrial corporation, to establish numerous experimental or developmental sections or departments in many different localities. These have been established as needed over a long period of years. The field covered by such experimental departments is co-extensive with the product.

Naturally, it has been impossible to confine all experimental work to definite physical locations or buildings. Much research work is of necessity carried out in the manufacturing departments, and especially in the so-called testing departments, the experimental work and the research work in such cases being under the charge or guidance of the interested, responsible engineer. While a large part of such work may be more properly called development, as distinguished from research, there is an astonishing amount of truly scientific research constantly going on in the electrical industry—research that scientists of note and reputation regard as satisfying the most exacting definition of scientific research.

The oldest experimental and research unit of the General Electric Company is located in Lynn, Mass., and is known as the Thomson Research Laboratory. This laboratory is the outgrowth of the Experimental Department which was started by Professor Elihu Thomson over 42 years ago. It has been the scene of many important industrial researches, discoveries and inventions, mainly due to the genius and industry of its founder. Among the notable achievements may be mentioned electric welding, investigations of alternating-current repulsion phenomena, flame arcs, constant-current transformers, lightning arresters, integrating wattmeters and others too numerous to detail.

At the present time, under the direction of Professor Thomson, a staff of about 20 is kept employed on research and development problems. On this staff are physicists and chemists, and mechanical and electrical engineers. The field of research and development covers problems connected with steam turbines, turbine-compressors, superchargers for airplanes, special alloys, fused quartz and its application to insulators, lenses, optical reflectors and other purposes.

At Pittsfield is located the largest factory for the manufacture of transformers for power purposes, ranging up to 20,000 kw. In its laboratories and experimental department, constant research has been carried on to improve the quality of the sheet steel used in transformers, and the oil used for insulating purposes.

Transformer oil, even of the very best quality, is subject to certain deterioration, called sludging, apparently as a result of oxidation. Research has been carried on for years to discover the exact cause, and a remedy for the disease. Much promising work has been done with substances called anti-catalysts. Tests of dielectric characteristics of a large number of oils and waxes are made, investigations of several years' duration are under way to determine the rate at which the mechanical strength of various types of insulation deteriorates when subjected to the normal temperature of operation. This is an endeavor to obtain accurate data in regard to the deterioration of organic materials under operating conditions.

In the high-potential laboratory at Pittsfield attempts have been made to reproduce artificially the conditions of a lightning stroke. Starting with 250,000-volt equipment some years ago, there is now in operation a 2,000,000-volt lightning generator, according to a design first suggested by Peek.

Early in the year 1923, lightning strokes of 2,000,000 volts to ground were for the first time in history artificially produced and controlled in this laboratory. These voltages are in excess of any hitherto produced, and are probably higher than those ordinarily produced on a transmission line by natural lightning.

Two-million-volts-to-ground lightning strokes can be obtained which increase at the rate of 50 million volts per second, while the power may be millions of kilowatts. The instantaneous value of the current may reach 10,000 amp. Naturally the results obtained are extraordinary. A discharge takes place with a very loud noise. Large pieces of wood are split with ease; glass, porcelain and hard rubber are easily shattered; fine wires are vaporized and sheet metal exploded or punctured. Though the lightning strokes in some cases last only a millionth of a second, the eye can perceive the corona produced within this time.

Perhaps the most interesting theoretical result has been a more accurate estimate of the voltage of a real lightning bolt. Tests made by this 2,000,000-volt generator would indicate that the ordinary voltage of a severe lightning stroke to ground may be about 100 million volts. If we assume that this corresponds to a discharge from a cloud about 1000 ft. above the earth, it would be equivalent to about 100,000 volts per foot, which indicates a very fair continuation, even for these high voltages, of the needle-gap curve first published by Steinmetz and afterward extended by Peek. Studies were made of the protective area of a lightning rod, and Franklin's theory that the lightning rod protects a definite area received experimental verification.

One may inquire how such industrial research could prove of value to the corporation which finances it. When originally started, it was justified on the ground that a better knowledge of such phenomena would extend the limits of long-distance electric power supply, and thus increase the demand for such electrical apparatus. It has already done this, and supplied data for improved design of such apparatus. It has also made possible important additions to our theoretical and practical knowledge of the dielectric strength of air and other materials.

In 1901 the General Electric Company felt the necessity of adding to its already existing laboratories and experimental departments a laboratory devoted to the definite purpose of undertaking research in pure science. Such a laboratory was started in Schenectady under the direction of Dr. Willis R. Whitney. The success of this laboratory in making important contributions to pure science, as well as in the creation of new products, is well known and does not need to be elaborated at this time.

Perhaps a concrete idea of the field for research which has already been found desirable may be obtained by considering subjects which have proved important enough to be placed upon a fairly permanent list in the field of work covered by this laboratory—items which have been the subject for research for years past and are likely to continue to be of interest for an indefinite period. A partial list is as follows:

Vacuum tubes
X-ray tubes
Electronics
Incandescent lamps
Kenotrons
X-ray spectrum analysis
Insulation
Ionization
Radio research
Vibrations and strains
Ferrous alloys
Non-ferrous alloys

One of the best examples of an industrial research laboratory, noted for the varied scope of its work, the revolutionary character of its output, and for the length of time which it has existed, is the famous laboratory of Thomas A. Edison. This was started in Menlo Park about 1875, and moved to Orange, N. J., about 1887, so that it has had a continuous history of nearly 50 years.

It was in Menlo Park that Edison conducted those remarkable researches and experiments which ended in giving the world not only the incandescent lamp, but a complete system of generation, distribution, regulation, and measurement of electric light and power, upon which has been based the development of our central-station electric industry.

From this laboratory also came the phonograph and the motion picture. It might be claimed that the phonograph was an invention of a great genius, and not the result of research methods, as now understood. Yet even so, its development has required the application of the best industrial research methods.

Also, if Mr. Edison could be persuaded to write the story of the development of his nickel-iron battery, it would, I believe, disclose one of the most interesting chapters in the history of industrial research.

It is interesting to note that the vacuum bulb, which Edison made a practical device in the incandescent lamp, is not limited in usefulness to the giving of light, but is the basis of a whole series of useful electrical devices. It is used in the rectifier for changing alternating current into direct current, and the reverse; and the same vacuum tube, through the Edison effect, discovered by Edison in 1883 and developed by Fleming, Deforest, Langmuir, and others, has become the basis of wireless telegraphy and telephony. This same Edison vacuum tube, in the hands of Langmuir, Coolidge, and others, may be destined to revolutionize our present method of transmission of electricity. Therefore, the vacuum tube of Edison, although

46 years old, is still one of the most interesting and promising of all the wonderful products of his genius.

Industrial research in the electrical business cannot be limited to the research laboratories, experimental departments, and the various manufacturing establishments. It is necessary to make experimental investigations of phenomena on a larger scale than can be provided in any laboratory or even in any works—for example, in the cases of such important pieces of apparatus as the steam turbine, the electric locomotive, and in many applications of electric motors in steel rolling mills and other large industrial operations. It is also necessary to investigate the electrical phenomena connected with the actual operation of long-distance transmission lines over great distances and high altitudes, and to observe the mechanical and electrical effects of short circuits in electrical systems carrying large amounts of energy, which may be determined only in the actual installation. Therefore the industrial companies frequently have been forced to extend their research work outside of their own premises and make use, when permitted, of the facilities of large users of electrical apparatus. Progressive public utility companies and manufacturers have recognized the benefit of such research work, and assumed their full share of the responsibility and risk involved in utilizing experimentally, when needed, the apparatus and other facilities. They have done even more by employing engineers and research men to carry on much of this work at their own expense.

The research departments of universities have also taken up such field work, as an interesting example of which is the work of Professor Ryan at Stanford University in California, on the study of corona effects and the losses as influenced by shape and size of cable on long-distance transmission lines. This is one of many illustrations of the overlapping of industrial and educational research in the experimental and industrial field.

The extent to which the movement for industrial research laboratories has grown in this country may be seen by consulting the bulletin of the National Research Council, which in 1921 published a list of over 500 industrial laboratories employing some 5000 chemists and physicists. This does not include laboratories connected with Federal, State or Municipal governments, or with educational institutions.

It must not be supposed that the benefits of the discoveries of the industrial research laboratory are confined to the company which bears the expense, the industry with which it is associated, or even to the country in which the firm is located.

It is usually the policy of industrial companies not only to permit, but to encourage the publication of their work by scientists in their employment. By this means the entire industry and the world in general are informed, and the diffusion of knowledge is increased.

As an instance, mention may be made of the publication of over 360 articles during the past ten years by 70 different members of our organization, under the auspices of the Research Laboratory. These range from articles covering purely scientific research, such as "The Structure of the Helium Atom," to descriptions of new and useful processes or applications, such as "The Application of the Photo-Electric Cell to Practical Photometry."

It may be of interest to mention that the General Electric Company, in the development of the electric locomotive for main-line service, found it desirable to build its own test track, four miles long, at its works at Erie, Pa. This is equipped with ample power for operating the heaviest locomotives, at speeds up to 100 miles per hour. On this track has been installed a new testing machine capable of measuring the vertical and lateral pressures exerted upon the track rails by each axle of a locomotive or car, at any speed. This testing device has been called the "Otheograph," and has been described in the technical press by W. B. Potter, its designer. Its use has already given valuable experimental information upon a subject about which little has been known. Tests have been participated in by the American Locomotive Company and by the professors of the University of Illinois.

The industrial researcher must keep fully abreast of all the disclosures and publications made by similar workers, either in pure science or in technical development, whether in this or in other countries, as every new scientific discovery must be carefully considered. A scientific library is, therefore, an essential part of the laboratory equipment, and it is of even greater importance that it should be fully used.

Mere reading is not sufficient. It is frequently desirable that the experiments, and to some extent the work, of other researchers should be repeated. It is necessary to have that intimate knowledge which comes from personal performance of the actual experiments. So it has been found useful to have as a part of the Research Laboratory a room in which may be set up duplicates of the latest or most important scientific apparatus; as, for example, Wilson's apparatus for showing the path of an alpha ray, or apparatus with which may be repeated such fundamental experiments as Milliken's determination of the charge on the electron, the fundamental unit of electricity. This equipment is available for the use of interested, qualified men, and is often used for educational purposes.

Research work is not always interesting to the outsider. It may easily appear most monotonous, as often experiment after experiment has to be repeated with only minute variations. Only the researcher may see its beauty and feel the joy of work well done when success crowns his efforts.

For instance, one of our research men has worked for 12 years on mixtures of tar, asphalt, pitch, and gilsonite and, as a result, has developed the foundation for most of the insulating materials which are now in use in the winding of coils for apparatus.

Again, two men have worked for ten years on improvements in carbon brushes, for electrical machinery—not very interesting or beautiful objects, but of great importance in our industry, as any improvement or deterioration in quality of such brushes may easily affect the capacity and performance of such large apparatus as synchronous converters, large industrial motors, or the countless motors used in transportation.

Dr. Whitney tells that "our research men are doing such apparently footless things as measuring the rate of flow of a black oil into a white one, when the only cause for any motion at all is an electromotive force impressed on the oils. This is related to researches on better high-voltage cables."

One can never tell in advance whether a new discovery or fact has any technical application of value. As one example of many, we may mention that Ramsey and Raleigh, about 1894, discovered certain gases in our atmosphere, among which was argon. These gases were chemically inert, and remained scientific curiosities for many years until Langmuir found that argon was the very thing that he required for use in his latest gas-filled incandescent lamp.

Also Laue, Bragg, and Moseley discovered that each element gave out a characteristic radiation when subjected to x-ray bombardment, and found in this characteristic radiation the so-called "X-ray spectrum," a phenomenon of great scientific interest, yet which offered at first no field for commercial application. Now x-ray spectrum analysis forms a part of the daily routine of the scientific industrial laboratory. Such analysis is used to discover the internal structure of materials. It even discloses the mystery of atomic structure. It is like an atomic microscope which enables us to see, for example, the effect of rolling or drawing upon the internal structure of metal, the changes produced by "fatigue" or strain, and the atomic structure of alloys. It has led to a beautiful explanation of the mysterious fact that the element carbon is hard in the diamond, and slippery lubricating material in graphite. It discloses "that in the diamond the carbon atoms are so located that each atom shares two electrons with each of its four neighbors in tetrahedral form, while in graphite carbon atoms are arranged in layers or separated sheets." Thus, we see from the nature of the molecular arrangement why the properties of carbon in the diamond and in graphite should be so different.

Scientists are now obtaining such definite information about atoms and molecules and their internal structures that they are learning to regard them as very real and definite things, differing not only in size but in form—some molecules are like marbles, some like bricks, others again like long rods, the dimensions of which are known with great accuracy.

In fact, we hear constant discussion of structures "one molecule deep," of so-called "molecular layers," similar to a brick or cobblestone pavement, and such ideas do not appear to be vague speculations, but practical enough to serve as the foundation of real technical advances.

Take, for example, colloids, which are small particles suspended in liquid (but not dissolved). Colloids are the basis of a new japan varnish, where the japan particles are suspended in water instead of being dissolved in turpentine or in naphtha.

Dr. Whitney says: "Here the japan is merely a fine suspension in water, kept in a permanent state of fine division by a modern process of stabilization which owes its efficacy to the fact that a substance is put into the mixture which forms a molecular layer on the surface between the colloid particle and the water. One picture of this process is that the chemical compound, which may be called the anti-catalyzer, is of such a nature that one part of its molecule dissolves in the colloid material, or absorbs on it, and the rest of the molecule dissolves in the water. In other words, chemical fences are interposed between the two substances, so that neither of them can completely aggregate." This water japan effects a considerable saving in manufacturing cost and offers the added advantage of lack of that fire hazard involved in the use of most volatile solvents.

Again, he says: "Now among the molecular-layer phenomena is that peculiar phenomenon of catalysis where the mere presence of a trace of some foreign substance makes some processes or reactions proceed which do not take place without the catalyzer, or at least, take place very slowly. More novel still are the cases of the anti-catalyzers, where a small quantity of some substances, apparently by its mere presence, prevents or reduces the rate of a reaction which would proceed much more rapidly without it. In the oxidation of many oils and similar chemical compounds such anti-bodies are known, and the problem is to introduce the proper ones into the special oils needing them, and this without introducing other complications."

As an interesting example of the extent to which industrial research becomes a creator of new devices and new industries, it may be mentioned that in one large electrical corporation a recent survey disclosed that about 15,000 men were engaged almost exclusively in the manufacture of products which were the outcome of the research laboratory. The value of the annual output was conservatively estimated at $60,000,000.

At one time an estimate was made of the benefit which the public received as the result of research in but one industrial field, namely, that of the incandescent lamp used in electric lighting. It was estimated that in 1920 the American people paid about $500,000,000 for the electricity that it used for such lighting. At that time the tungsten filament Mazda lamp was in general use. The question is: How much more would it have cost the people for the light that they actually enjoyed in 1920 if the Mazda lamp had been no more efficient than the carbon filament lamp? The answer is indeed startling: It would have cost an additional $1,000,000,000 at the lowest estimate—a difference of over one billion dollars a year in the cost of such electric light used by the country as a whole.

The amount of this remarkable saving is probably underestimated considerably. However, if we were to add to this amount the estimated value of the results already obtained in all the other manifold fields of electrical manufacturing, the achievement just mentioned would represent but a small portion of the benefit which the American people have received as the result of industrial research and its technical application.

Similar scientific methods of research have been applied by the public electric utility companies under the direction of their leaders in finance and engineering, and have been largely responsible for the remarkable growth of that business, and the unequalled service it renders the public. The methods and results achieved have been fully published on many occasions, especially by that great pioneer and leader, Dr. Samuel Insull.

History shows that industrial progress has been often dependent upon the energy and genius of some great individual. In the future advances will undoubtedly come in the same way, but we believe that more frequently the greatest progress will follow the use of organized research, and from co-operative efforts of men in the universities, industrial corporations, and national institutions. Science is international. Its field is the world. Information is freely exchanged, there is no tariff on scientific ideas, and progress is based upon the work of workers in every civilized land.

Rutherford says: "The unknown appears as a dense mist before the eyes of men. In penetrating this obscurity we cannot invoke the aid of supermen, but must depend on the combined efforts of a number of adequately trained ordinary men of scientific imagination. Each in his own special field of inquiry is enabled by scientific methods to penetrate a short distance, and his work reacts upon, influences the whole body of other workers."

Is it not possible that there is a real danger that the wonderful success of science may be the means of her undoing? The constant succession of modern miracles is making us callous to their reality and value. May not our very familiarity breed indifference, if not contempt?

We have long lost the thrill inspired by the telegraph and the telephone, the airplane and the automobile, the x-ray and the electric light. Even the radio is a commonplace. We think nothing of hearing a human voice speaking to us across the sea.

Is it not desirable occasionally to stop our daily task long enough to review the wonderful record, to realize that our progress is not due to chance of lucky "rule of thumb" methods, but is the result of ceaseless activity and hard work by many earnest men, following the scientific method of research?

The scientific method has accomplished such wonders in industry that it is to be hoped that the value of its spirit and method will soon come to be more generally recognized and appreciated, and applied in other fields of human endeavor.

Therefore, why should not the scientific method and spirit which has shown itself so effective and powerful when applied to material things prove equally effective and powerful if applied to the relations of men to each other in organized society—in the economic and even the political arena?

It would appear to be a reasonable proposition that in such fields it is equally desirable; that freedom from prejudice, careful observation, honest and truthful interpretation, the essence and spirit of scientific research, should be practiced, and if adopted, that a basis would soon be discovered for that better understanding and knowledge needed for a true and lasting peace, and for the highest intellectual and spiritual development of man.

The Charles A. Coffin Foundation Award to the Northern Texas Traction Company

The Charles A. Coffin gold medal for outstanding contribution to the art of electric railway transportation was this year granted to the Northern Texas Traction Company, at the recent American Electric Railway Association Convention at Atlantic City.

In making the analysis of the various competing railway companies, eight factors were considered:

First, the initiative, skill, and enterprise in winning the public to electric railway service.

Second, the outstanding success in gaining public goodwill.

Third, the economies in operation resulting from original ideas.

Fourth, the economies in operation which demonstrate the extent to which the competing companies took advantage of new developments in operating and maintenance practice, and in equipment.

Fifth, the improvements in construction practice resulting in reduced first cost or maintenance, or tending to greater reliability of service.

Sixth, the success in conducting safety program campaigns and the reduction in the number and seriousness of accidents.

Seventh, the outstanding accomplishments in the development of good relations between management and employees.

Eighth, the special attainments in financing which reduce the cost of new capital, such as the distribution of securities among customers and employees, etc.

The Northern Texas Traction Company has been unusually progressive in its advertising campaigns. Short-haul real estate development has been intensively undertaken in connection with advertising in newspapers, slogans, etc.

Public goodwill was fostered by a constant activity which resulted in large public interest. Bus competition was successfully met.

One-man cars are used exclusively, these having been "sold" to the public through an educational campaign. By distributing split rings, the use of tokens without price reduction was increased from 1400 to over 6000 daily.

The origin and practice of many economies resulted in a reduction of the costs of labor and kilowatt-hours per car-mile, and of maintenance and structure per car-mile. In the line of accident reduction, monthly meetings of the employees were held by the company. Trainmen's performance was carefully analyzed and considered. Some streets were widened for new car lines in order to decrease accident hazards, and warning signs were placed over dangerous street intersections.

In considering employees' relations, the committee of awards found that the Northern Texas Traction Company had never had a serious difference of opinion between employees and management. Among the factors responsible are: benefit society payments increased; annual physical examination and "preventative" medicinal treatment; group insurance; vocational education; discussion of A.E.R.A. convention proceedings; special bulletins; prizes for trainmen's suggestions on new business methods; annual parties and special cars for employees' parties.

The Northern Texas Traction Company has had a large sale of securities to its employees and the public. By virtue of instituted economies, financing for 1924 was possible from the earnings of the system.

This is the second company to receive an annual award in the electric railway field from the Charles A. Coffin Foundation, which was established in 1922 by the General Electric Company. The winning company last year was the Chicago, North Shore and Milwaukee Railroad.

The Remote Operation of Valves and Gates

By R. H. Rogers

Industrial Engineering Department, General Electric Company

Since its initial application electricity has been steadily removing the burden from human hands and doing the work in a faster and more efficient manner. The ability to control this great force from a distance has been one of its outstanding features. In this article the author deals with the service of electricity in the remote operation of valves and gates. An unusually interesting example of this application of electric power is illustrated at the locks of the New York State Barge Canal, where the control of the valves and gates stands out in sharp contrast to the manual operation of those of the Erie Canal. Some of the factors, which must be considered in the design of equipment for this service, are touched upon. Provision is made on nearly all valves and gates for hand operation; but the fact that in most cases this means has never been employed is mute evidence of the reliability of the electrical equipment. This method of control is daily finding more widespread application.—Editor.

Those who have navigated both the old and the new canals of New York State are in a unique position to appreciate the service of electricity, but similar opportunities for comparison are becoming rare because such radical changes are not now common in the normal observation period of one's life. The remote operation of valves and gates adds much to the appeal of the modern method, for we see the uniformed operator at a vantage point in full control of all the elements of the locking cycle by means of a group of small handles conveniently placed for his use.

The approach to a modern lock especially at night is safeguarded: first, by electric buoys; second, by the general lighting of the lock vicinity; and third, by a system of colored lights in columns which indicate the position of the gates and the state of the water level within the lock. This level, some 14,000 sq. ft. in area, is raised in some cases over 40 ft. by admitting water through two gate valves, 10 by 12 ft. in size, located deep in the concrete walls at each side at the upper-level end. The water is discharged to the lower level by similar valves at the lower-level end of the lock walls.

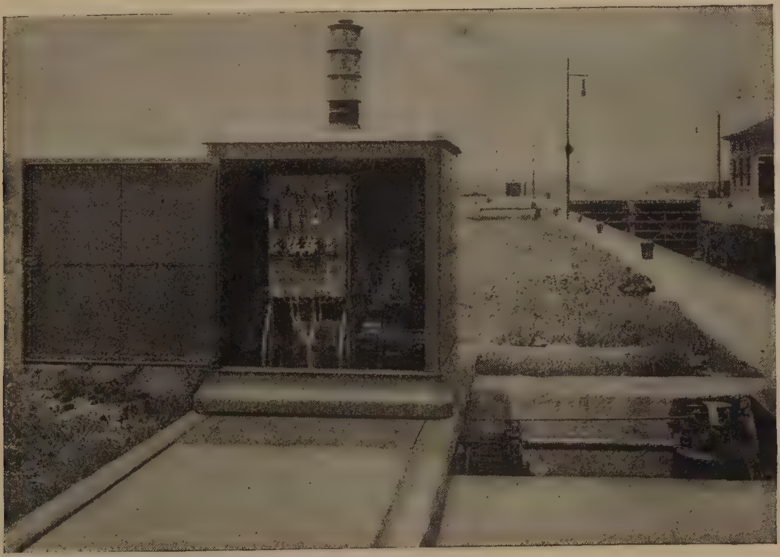


Fig. 1. Valve-motor "House" Surmounted by Signal Lamps Behind Fresnel Lenses

These valves are operated by heavy enclosed mill-type motors through trains of gears, and are controlled by magnetic contactors on panels housed with the motors in neat enclosures on the lock walls. Columns of colored lights show the valve positions and thus indirectly the lock water level. Fig. 1 shows a valve-motor "house" surmounted by the signal lights behind Fresnel lenses.

The massive lock gates, two at each end and each weighing nearly 100,000 lb., are swung to and fro by great arms leading into the walls to invisible but obviously powerful mechanisms. Having a width of 25 ft. and immersed 12 ft. in water, the gates meet with great resistance to which inertia and the friction of the giant hinges are added.

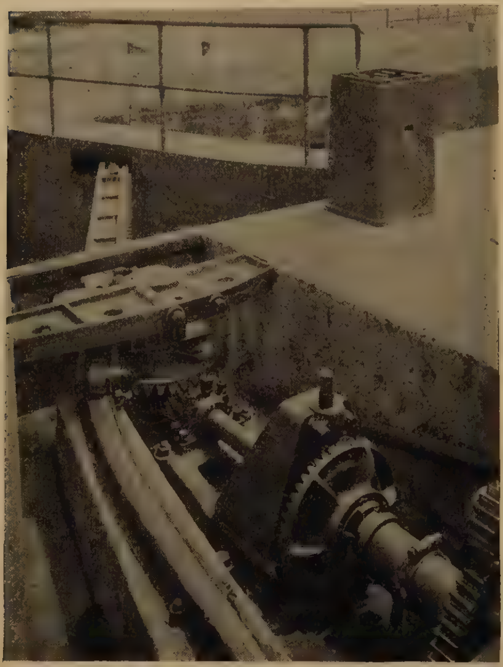


Fig. 2. Part of Gate-swinging Mechanism. One of the operating stands at which valve and gate controls are concentrated is shown in the upper right

A slight movement of a handle the size of a pocket knife serves to swing a gate through 90 deg. to its seat without jar and without danger to boats as the swing is under perfect control through the entire arc. Fig. 2 shows a part of a gate-swinging mechanism, together with one of the operating stands at which the valve and gate controls are concentrated. The first reduction gearing, a gate motor, and its control panel are shown in Fig. 3 in which are also illustrated the gate-position indicating lights which are so useful to a heavy fleet approaching at night.

Fleets are locked through in from 10 to 15 minutes whereas in the old-style lock at least a half-hour was required to put through one small boat.

Guard gates and water-level control gates are adjuncts of the canal system which lend themselves to remote control. Guard gates, counterweighted with concrete blocks, are moved vertically in guides. The motors are high up on the superstructure, while the control, of the master-switch magnetic type, is located either at a nearby lock or in a station where water and navigation conditions may be readily observed.

The modern floating dry dock presents some trying problems in hydraulic stabilizing that have been successfully solved by the remote control of flood gates. Such a dock is made up of a number of U-shaped articulated sections each containing several water compartments. To submerge the dock for the purpose of receiving or discharging a ship, water is admitted to the compartments through perhaps 36 flood gates, or valves of the gate type.

Longitudinal and traverse trim and equilibrium must be maintained, and all the sections must sink at the same rate and without tilting, otherwise the inter-fastenings are likely to yield and in extreme cases the dock and its burden of ship or ships may capsize.

Substantial outdoor valve stands with gearing and motors are located on the decks over the gates which are reached by long vertical rods threaded at the stand. The controls for all these motors are concentrated on a push-button board at the head of the dock on shore, where the operator can see

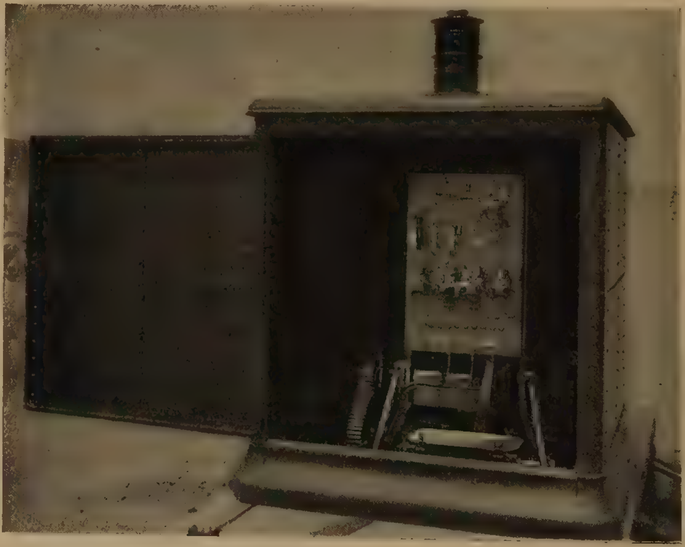


Fig. 3. A Gate Motor, Its Control Panel, and First Reduction Gearing Mounted in a House on Top of Which Are the Gate-position Indicating Lights

the dock master's signals. A dial beside each push-button station indicates the depth of water in the compartment to which that control is connected. In some cases the operator wears a telephone head-set connected to a portable transmitter in the hands of the dock master, thus insuring communication under all circumstances. A flood-gate stand is shown in Fig. 4; a control station for 36 of these stands is shown in Fig. 5; and the contactor panels for these and for twelve pumps are shown in Fig. 6.

Graving docks make extensive use of remotely operated sluice gates and valves, although in this type of dock the functions are not as complex as in floating docks. At some of the larger docks, the control is of the manually operated oil-switch type concentrated on a board in the power-house at the head of the dock.

Hydraulic works such as hydro-electric plants, irrigation projects, and city water works take advantage of remote operation of valves and gates for safety, for convenience, for automatic functions, or for all three reasons. A good example of a hydro-electric application is found at the Sherman Island hydro-electric plant of the International Paper Company, near Glens Falls, New York. Five 10,000-h.p. turbines are fed by fifteen 10 by 11-ft. concrete penstocks 250 ft. long. The 15 gate hoists, 12 of which are shown in Fig. 7, are located in the head-gate house over Broome caterpillar gates.

They are controlled individually by local push-buttons and reversing magnetic-contactor panels. A small panel in the power-station operating gallery affords control by groups of three, that is, a control for each turbine. Signal lights on the panel show the position of the gates. This small panel is shown in Fig. 9, mounted on the wall at the right.

Penstock needle valves for high-pressure and butterfly penstock valves are operated by remotely controlled motors through gearing, the use of a non-traveling nut working about a traveling stem being a common last-motion expedient.

When we enter the field of automatic power stations we find the principles of remote control so refined and extended as virtually to give the station a mind of its own. Here in brief is a sequence of events in such a station:

> The contacts of the float switch close when the water in the forebay has reached a predetermined level.
>
> The relay thus energized closes the gate motor contactor and starts opening the waterwheel wicket gate.
>
> At a position of 20 per cent gate, the waterwheel is running. The motor is then stopped by the opening of its contactor by the drum switch geared to the gate motor. When the waterwheel is nearly up to synchronous speed a centrifugal switch recloses the contactor and the gate motor resumes opening the gate.
>
> The geared drum switch now performs the necessary operations incident to putting the generator on the line and in addition stops the wicket-gate motor.
>
> When the water reaches a predetermined low level, the station is automatically shut down by the closing of the wicket gates. This is accompanied by the restoration of all the relays and contactors to the condition necessary to safeguard the station in restarting.

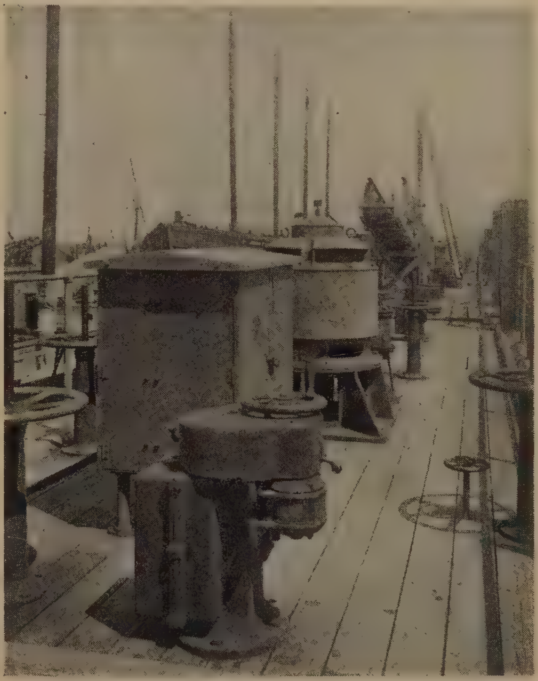


Fig. 4. Floodgate Motor, Pump Motor, and Enclosed Control Panel. Push button control is located at the head of the dock for thirty-six flood-gate and twelve pump motors

The flume head gates call for a massive construction and large motors, as indicated in Fig. 8, which shows a means for operating two head gates from one motor. A single similar equipment is shown in Fig. 10.

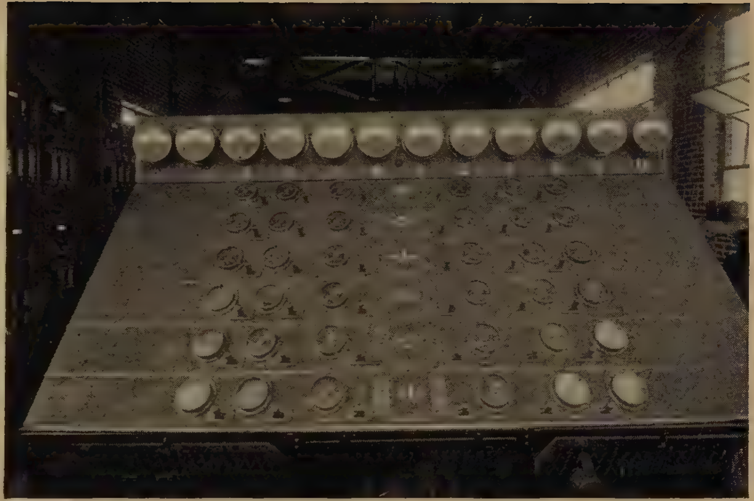


Fig. 5. Control Station for Thirty-six Floodgate Stands

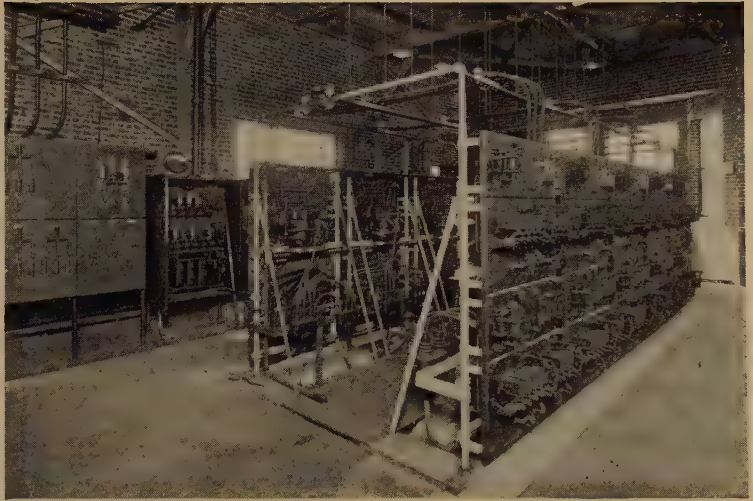


Fig. 6. Contactor Panels for Thirty-six Floodgate Stands and Twelve Motor-driven Pumps

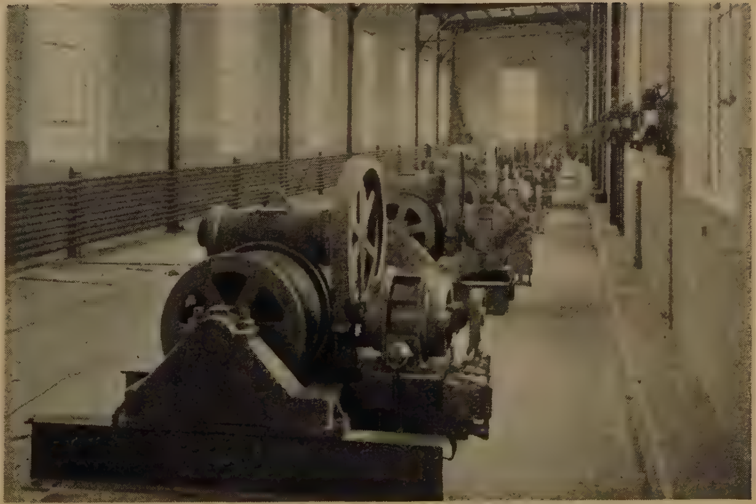


Fig. 7. Twelve of the Fifteen Gate Hoists Located Over Broome Caterpillar Gates at the Sherman Island Hydro-electric Development

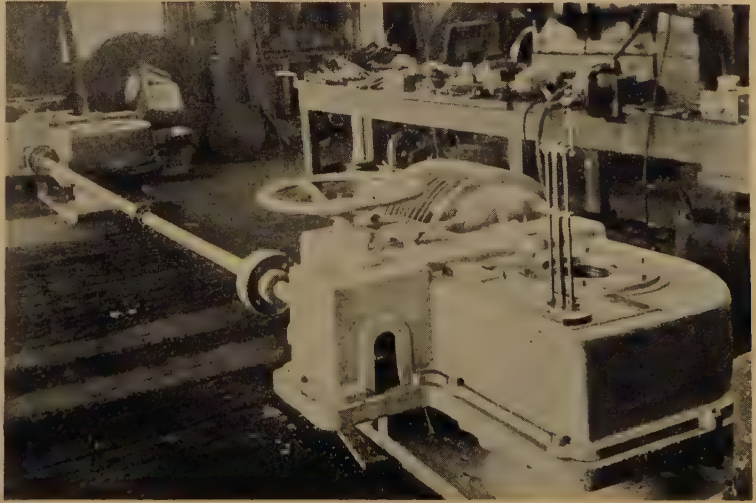


Fig. 8. Equipment for Operating Two Flume Head Gates by One Motor

A 42-in. gate valve for a 100-ft. head of water is shown in Fig. 11 and represents a type frequently used with remote control for irrigation works, city water works, and graving docks.

Movable weirs for regulating storage-stream flow are becoming common, particularly in Europe. They take the form of hinged-sector gates, or of rolling-gate weirs. Some of the sector gates are of great size, the writer's attention being recently called to one 177 ft. long having a 15-ft. chord. They are built and housed so as to make use of flotation to effect the necessary movements. The height of the water within the chamber below the sector and hence the degree of sector elevation is regulated by a telescoping overflow. A small electric motor with push-button control serves to raise and lower the telescoped discharge pipe, thus putting this huge mechanism under push-button control. In some cases float-switch control is used to render the system entirely automatic.

Roller weirs are great steel cylinders having gears at both ends that roll in inclined racks thereby insuring alignment. The stream regulation obtainable equals the diameter of the cylinder and this, in one case at least, is 42 ft. A chain passes around the drum in the manner of a rolling hitch, or "parbuckle," thus enabling a motor winch to adjust the water level quickly by rolling the cylinder up or down the inclined racks.

At Raanaasfoss, Norway, there is a rolling gate 148 ft. long and over 21 ft. in diameter which is operated by a 40-h.p. motor geared to 500,000-lb. lift. This gate is under remote control from the power station.

By way of contrast, attention is called to the one-inch solenoid-operated valve in Fig. 12, which is opened and closed by a simple switch or other contact-making device that may be actuated by pressure, liquid level, or temperature. Valves of this type find many uses. For instance, in the logging industry the "whistle punk" carries a portable push button on a long lead, by means of which he can blow signals on the logging-engine whistle while huge logs are being snaked, sometimes a quarter of a mile, through the woods from the "choker setter" to the log-loading station.

Cooling water or brine for various purposes is conserved by such a valve under thermostatic control or the content of tanks is maintained between certain fixed levels by float-switch control as shown in Fig. 13. An interesting application is found in the secondary control by this means of heavy dampers, valves, or gates manipulated by compressed air or by hydraulic pressure. Such applications are found in tunnel-ventilation, and in the large balanced valves of the major hydroelectric plants.

The selection of apparatus and its proper application for the remote control of valves and gates involves many factors; safety and certainty of operation being paramount because of the great forces and complicated functions with which the practice is usually associated. Motors must be selected that have characteristics suited to the starting and running torques required, and that are safeguarded against moisture, salt air, or other detrimental factors likely to be encountered in the location of the installation. In addition they must be so constructed and lubricated that successful operation will be a certainty after prolonged periods of idleness.

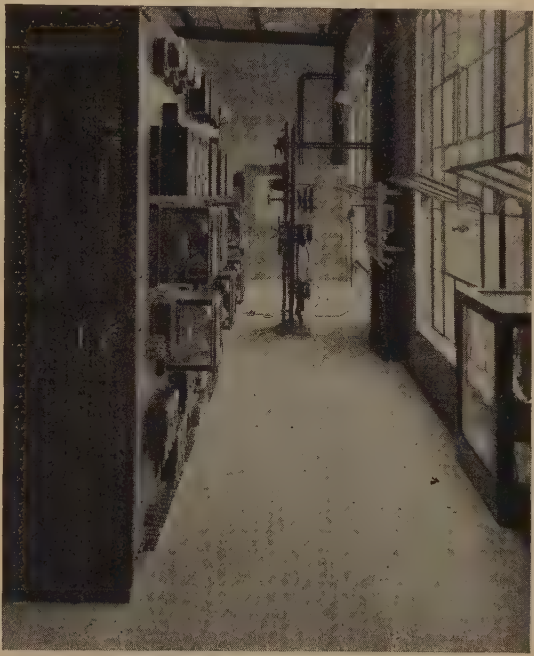


Fig. 9. Head Gate Control Push Buttons Are Located on the Small Panel Mounted on the Wall at the Right

The control systems are varied greatly by the functions desired, ranging from the simple switch for the solenoid valve to the motor-driven drum controller and complex interlocking control panels of the automatic hydroelectric station. The most common and useful control unit, the reversing magnetic panel with push-button control, is shown in Figs. 14 and 15, and a characteristic diagram of connections in Fig. 16.

An important element of the control in most of the applications mentioned is the limit switch which prevents jamming beyond the torque of the motor to release. These devices are designed to stop the motor at the end of the gate or valve travel, and to leave the connections closed for the reverse motor movement. As an additional precaution, in many instances slip-friction couplings are used. They are designed to prevent the hopeless jamming or the wrecking of the mechanism in case of the remote possibility of limit-switch failure.

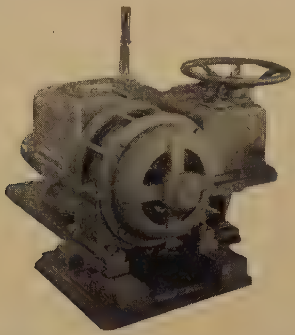


Fig. 10. Apparatus for the Control of a Single-flume Head Gate

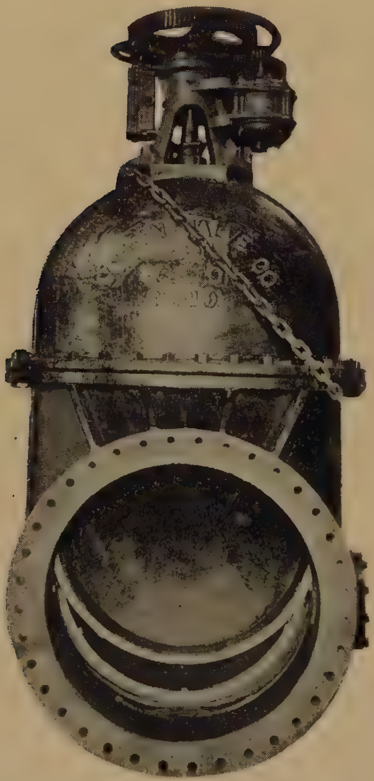


Fig. 11. Motor-driven 42-in. Gate Valve for Operation Under 100-ft. Head of Water

Nearly all valve and gate mechanisms, even including the giant rolling gate and the 50-ton lock gates, are provided with means for hand operation in case of a power failure. This method in some cases involves hours of labor by many men as contrasted with the normal operation which takes but seconds

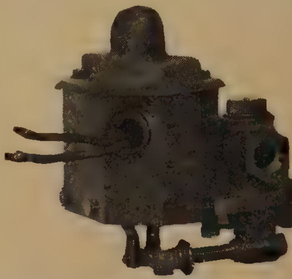


Fig. 12. One-inch Solenoid-operated Valve for the Remote Control of Liquids and Gases Under Pressure

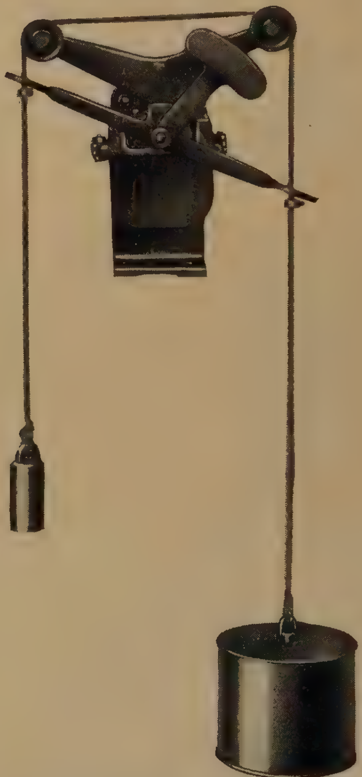


Fig. 13. Float Switch for Maintaining the Level Between Certain Limits in Tanks or Pits

and is accomplished by one finger. The fact that these hand mechanisms in innumerable cases have never been used speaks well for the reliability of electric power, motors, and controls, as they are now applied.

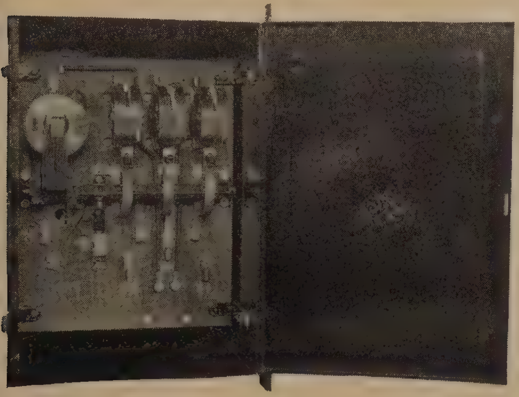


Fig. 14. **A Reversing Magnetic Panel with Push-button Control**

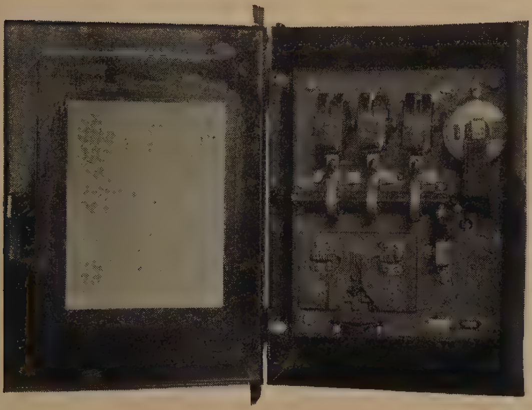
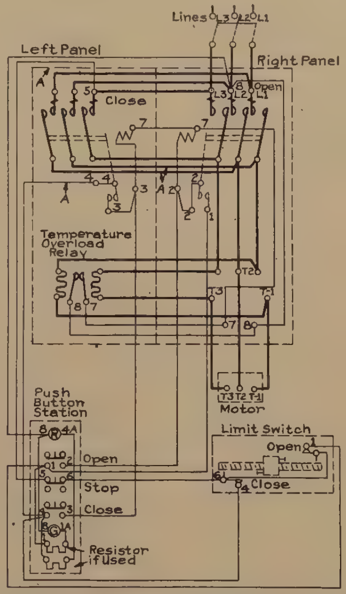


Fig. 15. **Another Type of Reversing Magnetic Panel with Push-button Control**

Interlocking between two or more stations from which a single unit can be worked, as well as interlocking with pressure, level, temperature, voltage, load, or any other conditions intimately connected, presents a varied field for ingenuity and depends upon the individual requirement. The difference of opinion as to the expediency ~~of~~ of clever automatic safeguarding or of reliance on the human element leads to compromises that vary with each extensive application.

The protection of inter-wiring from moisture and from mechanical damage is very important; while the source of power for the motor and control excitation requires extensive study to insure the permanence of power under all circumstances including emergencies when it may be most needed. "Sneak circuits" are a possibility in many complicated wiring layouts and thorough study is required to avoid such a possibility.



Note: Control is Made up of Two Panels Back to Back. Horizontal Lines Represent Studs Through the Panels Excepting Lines Marked "A"

Fig. 16. **Characteristic Diagram of Connections for Reversing Magnetic Control Panel**

Remote control is one of the many useful adjuncts of electric power that is not approached by any other means of power transmission, and as a result is daily finding new and ingenious applications. The general principles will remain as stated, but the working-out of specific applications presents an attractive field for the engineer with the certainty of its being of valuable assistance to the ultimate user.

The Importance of Standards in the Evaluation of Insulating Materials

By Lawrence E. Barringer

Engineer of Insulations, General Electric Company

To make it easy for electricity to flow along a desired path by furnishing a good conductor is not alone sufficient. Difficulties must be placed in the way of its escape to undesired paths, and this is the function of insulation. To accomplish either purpose most effectively necessitates an intimate knowledge of the materials used; their inherent properties, their actions under a variety of conditions, and a comparative evaluation of their utility. Such information about conductors is available to all designers of electrical equipment but this is not true of insulating materials. Mr. Barringer says: "This is not due entirely to either negligence or opposition on the part of the insulation manufacturer but largely to the great difficulty of formulating tables of properties which can safely be used either for comparison or for determining the form and amount of insulation to be used." Intensive work on the subject during the last few years has just about come to fruition and in an early issue we hope to publish results in the form of standardized tests. Considering the great rapidity with which the art of electrical design has already advanced, how much faster will it progress when such knowledge is generally available.—Editor.

Scores of insulating substances and compounds in literally hundreds of forms are today employed for the insulation of copper and iron in the construction of electrical apparatus. The field includes such well-known materials as mica, porcelain, glass, slate, marble, asbestos, varnishes, enamels, paper, cloth, molded compounds, asphaltic and resinous filling or treating compounds, rubber, and both mineral and vegetable oils.

In each of these classes there are produced a large number of forms or modifications to adapt the material to particular assembly and service requirements. For instance, mica may be simply cut or punched from the natural plates and used alone, as in rheostat washers; but in most cases the mica splittings are pasted or built up with spirit varnishes, to produce rigid mica insulation as in commutator segments and cones, etc., or to produce flexible mica sheet and tape for armature coils, transformer insulation, etc. There are thus a number of forms of mica insulation, some made with amber mica, some with white mica, some rigid, some flexible, and varying from pure mica to mica cemented to papers of various types to form composite insulations. Similarly, insulating varnishes may be black or clear, air-drying or baking, soft and flexible for coil insulation or hard finishing varnishes for dust protection as well as insulation. Every type of insulation is used in many forms and thus the entire field of insulating materials is so extensive and varied that the designing electrical engineer is often confused in his endeavor to select the materials best suited to the insulation requirements of the particular apparatus in which he is interested.

This varied and complex group of materials has gradually been developed as the result of increasingly varied demands made on electrical apparatus, these demands often being of a conflicting nature impossible of fulfillment by a single material. In some cases insulation must be rigid and strong to serve as a supporting medium as well as insulation (as in porcelain insulators for disconnecting switches or bushings for transformer leads); whereas in other cases insulation must possess a maximum degree of flexibility (as in magnet wire or in armature coil insulation). Heat conduction is often highly desirable to carry the heat away from the windings, as in armature coils; whereas heat insulation is sometimes required, as in retaining the heat in certain electric appliances as ovens and furnaces. Abrasive wear is required when the insulation must wear down uniformly with the conducting components as in commutators and the older types of magneto distributors; but, on the other hand, the dead segments of starting boxes or rheostats should indefinitely resist abrasion by the contact arm.

It is this diversity of requirements that has largely caused the development and use of the present large number of insulations; but it is not only the design and efficiency of electrical machines and appliances which demand insulation of many types and modifications but also the operating or service conditions.

The conditions under which electrical apparatus is to be employed often dictate the form of insulation to be used, aside from the design and efficiency demands of apparatus at the test room.

For motors or other electrical equipment used in mines, the insulation must not only be resistant to dampness or moisture but must very often resist mine water of an acid nature which is very injurious to some types of insulation. In metal mines there is also the possibility of the abrasive action of dust and the conductivity of metallic particles. In carbon plants, coke plants, boiler rooms and factories where powdered coal is used, the insulation of electrical apparatus is subjected to electrically conducting dust which frequently covers the windings and upon becoming mixed with oil or water may find its way into the innermost parts of the machine. In such cases insulation must be devised which has a hard resistant surface and from which the dust may be readily removed before being carried into the inner parts of the machine. The iron dust encountered in machine shops where dry milling is carried on is likewise to be guarded against by the form and arrangement of insulation. One of the most severe conditions for electrical apparatus is in chemical plants where nitric and sulphuric acid vapors and sometimes the acid solutions themselves are encountered. In some factories caustic soda liquor splashes upon motors operating the equipment.

Many examples could be cited of the severe and extreme conditions to which electrical apparatus is often subjected in service, including in addition to the cases named in the preceding paragraph, those conditions encountered in the operation of steel mills, beef packing plants, fertilizer factories, cement mills, refrigeration plants, ships, pumping for dry docks and irrigation projects, etc.

With each advent of a new material it is always hoped that the new insulation will supplant a number of those already existing, thus substantially reducing the number and simplifying the matter of choice or selection. Unfortunately each new material has simply taken its place in the steadily growing list, of course partly replacing other materials but never completely displacing those previously used. For example, when black plastic varnish was first developed it was anticipated that all insulating varnishes would eventually be of this type. Now, after 15 years or more since black varnish was brought out, yellow or clear varnishes are still employed and are preferable for some purposes, as for transformer coils that are completely immersed in mineral oil. The development and application of phenolic synthetic resins to insulation was likewise expected to result in displacing hard rubber and shellac compositions but both of these latter are still in use. All three have a place, although hard rubber is not used to nearly the extent it was before.

Since the many varied requirements of service cannot be fulfilled by a few materials only, and such a large number is necessary, the matter of choice or selection has become rather difficult. It often happens that the proper or best material is not chosen at the outset, as is revealed by subsequent service tests which indicate the necessity of better insulation.

The designing electrical engineer usually has not available sufficiently reliable data upon which to base his choice of material, particularly if he is buying it in the open market or selecting it from the field of commercial materials generally available. This is not due entirely to either negligence or opposition upon the part of the insulation manufacturer but largely to the great difficulty of formulating tables of properties which can safely be used either for comparison or for determining the form and amount of insulation to be used.

The selection of insulating materials has been largely based upon experience gained in cut-and-try methods, but in the past few years testing of a more general and uniform nature has been carried on with a view to establishing the specific properties of the materials most generally used.

However, even the testing of the past few years has been carried on in a hap-hazard manner without regard to correlating the tests with those made upon similar materials by other investigators. Usually the engineer or builder of electrical equipment conducts tests improvised to determine the suitability or unsuitability of the material for his particular purpose, and the results are not ordinarily of value to those interested in other types of apparatus or fields of service.

In testing work, insufficient consideration has been given to the effect of various conditions upon the resulting values. Temperature, humidity, thickness of specimen, time period of voltage application, frequency, pressure of electrodes, and other conditions all have a marked effect upon the values obtained and unless these conditions are reported with the results the latter cannot be taken as strictly indicative of the true comparative value of the insulation.

To illustrate the difference in results under varying conditions, several cases will be cited of tests made upon certain insulations with progressive changes in one of the conditions of the test. For the purposes of this article, the exact sources of the materials need not be described and it will suffice to say that all are standard commercial materials made by reliable manufacturers and truly representative of the various types of insulation discussed.

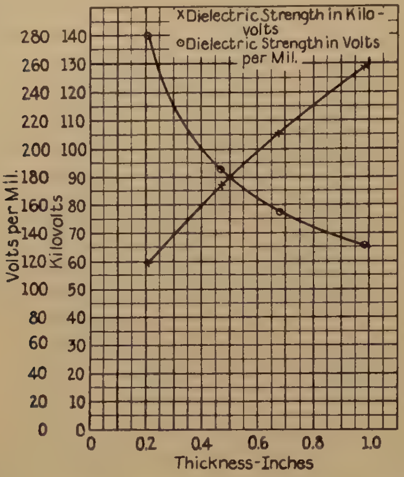


Fig. 1. Dielectric Strength of Wet Process Porcelain at Different Thicknesses. Tests made under oil at 25 deg. C., 60 cycles, using 1-in. spherical electrodes. Voltage raised at rate of 1 kv. per second

It is of course well known that the dielectric strength of insulating materials per unit of thickness varies with the thickness of the sample tested, and yet often claims will be made that certain insulations will stand so many volts per mil or per quarter inch without any reference whatever to the form or size of specimen.

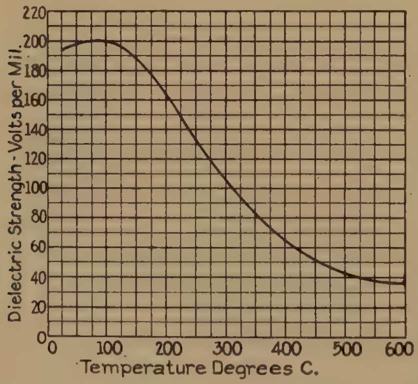


Fig. 2. Decrease of Dielectric Strength of Wet Process Porcelain with Rise of Temperature

The curves in Fig. 1 indicate the dielectric strength of standard wet process porcelain of different thicknesses, all conditions except thickness being kept constant. The dielectric strength of this porcelain may therefore be reported as low as 120 volts per mil or as high as 260 volts per mil, depending upon whether the specimen tested was approximately 1-in. thick or ¼-in. thick. The manufacturer would naturally like to report the higher figure but in so doing might mislead the user intending to employ a bushing made of considerable thickness for mechanical reasons aside from insulation.

Fig. 2 shows the decrease of dielectric strength of standard electrical wet process porcelain with rise of temperature; and Fig. 3 shows the effect of increasing temperature upon the dielectric strength of No. 31 Compound, a refractory, porous, ceramic composition used by the General Electric Company for cylinders or spools in devices subjected to wide and abrupt temperature change. This property of insulations is also generally well known, and yet but few tabulations of the dielectric strength of materials make reference to the temperature of test or even state whether all materials were tested at identical temperatures. Frequently designers have prepared tabulations for temperature correction of materials used in special apparatus, and in wire and cable work it is quite common to have tables prepared showing the relative insulation resistance of standard cable wrappings at various temperatures.

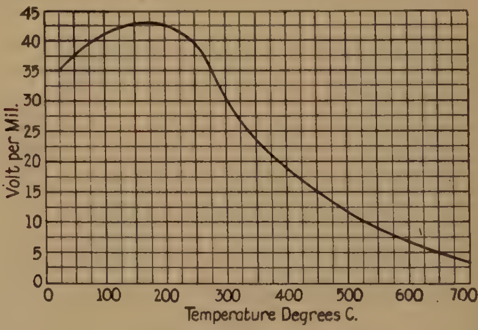


Fig. 3. Decrease of Dielectric Strength of G-E No. 31 Compound with Rise of Temperature

The decrease of insulation resistance as the temperature rises is particularly rapid in those materials where sustained values are most desirable as in cloths and papers, both treated and untreated, as used for wire and cables, armature coil insulation, etc. This is shown in Fig. 4 covering tests upon taped bars, using black varnished cloth tape in commercial use. Fig. 5 illustrates the same characteristic in wet process electrical porcelain, a rapid decrease not taking place until comparatively high temperatures are reached.

Fig. 6 indicates the variation in values for power-factor and dielectric constant of Bakelite-paper panel board used in radio apparatus where such values are of importance.

The importance of the control of humidity in testing porous materials, such as paper and cloth, has probably not been sufficiently realized until quite recently. It is true that most investigators have tested dried samples but they have not always taken into consideration that such specimens, particularly paper, re-absorb in a few seconds an amount of water almost equal to the quantity expelled. Often before the tests can possibly be applied the percentage of moisture has increased in the specimen to such an extent that the drying has been rendered quite a useless and misleading step in the procedure. Conversely, paper transferred from an atmosphere of high humidity to one of low humidity will, within a very few minutes, lose a substantial percentage of the contained moisture. Porous materials are so susceptible to these changes in relative humidity that testing only in a closed room in which the humidity is controlled, and kept uniformly at a certain point, will insure results strictly comparable as to definite values.

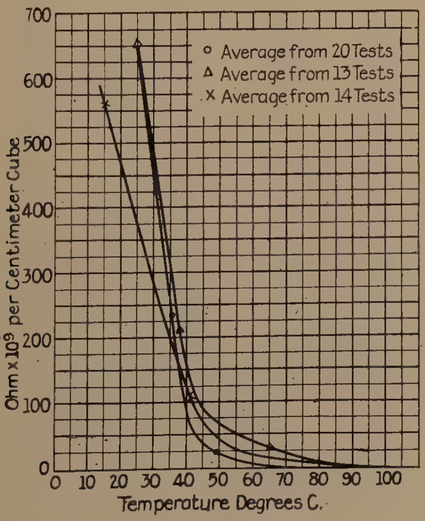


Fig. 4. Decrease of Insulation Resistance of Black Varnished Cloth with Rise of Temperature

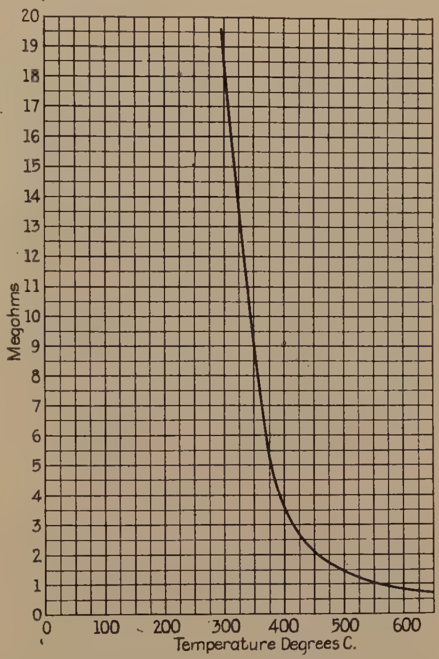


Fig. 5. Decrease of Insulation Resistance of Wet Process Porcelain with Rise of Temperature

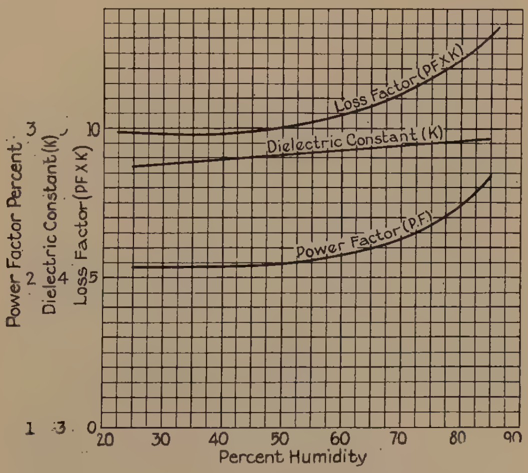


Fig. 6. Increase of Power Losses of Bakelite-paper Compound with Increase of Humidity

If relative humidity so affects the insulating values of porous materials, it is obvious that actual immersion in water must do so even to a greater extent and for apparatus to be exposed to water, as railway motors, pumping machinery, and certain marine devices, dry values alone cannot be accepted as indicative of the fitness of the insulation for the service.

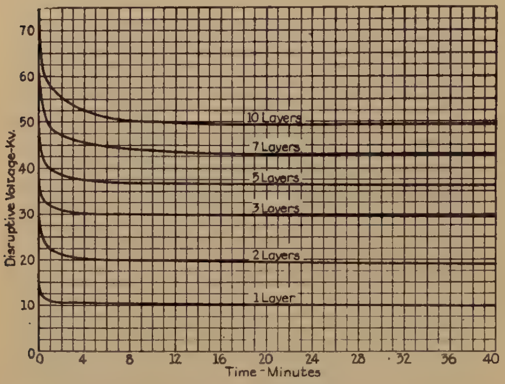


Fig. 7. Dielectric Strength of Black Varnished Cloth as Affected by Rate of Voltage Application

The effect of time of application of voltage upon puncture is illustrated in Fig. 7 where the material is black varnished cloth tested in various thicknesses (secured by multiple wrappings or tapings), and in Fig. 8 where the material is wet-process porcelain.

That pressure of testing electrodes has a pronounced effect upon the breakdown voltage of presspahn is indicated in Kinzbrunner's curve* shown as Fig. 9.

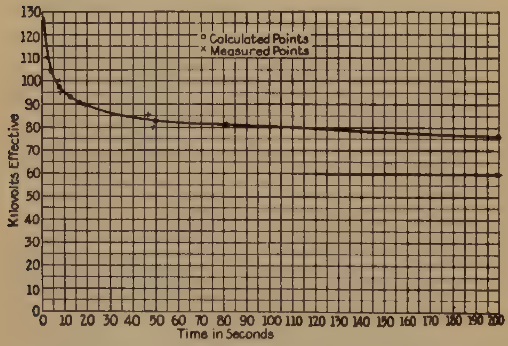


Fig. 8. Dielectric Strength of Wet Process Porcelain as Affected by Rate of Voltage Application. Tests made under oil upon porcelain with ¾-in. walls, frequency 60 cycles, sine-wave voltage

When testing for and reporting volume resistivity the voltage applied must always be considered, the effect of voltage upon the resistance of a wet-process porcelain tube being shown in Fig. 10.

Air as a dielectric is affected by the various conditions affecting other insulations and also more largely by difference in density than the solid and liquid materials. This variation in the insulating properties of air affects certain properties in insulators, particularly surface resistivity and arc-over voltages, and the results of tests for such properties should be accompanied by a statement as to relative humidity and air density (or altitude).

Not only the insulating properties but also the physical properties of materials may be affected by difference of temperature, humidity, etc.

The crushing strength, transverse strength, and impact resistance of molded insulation or rigid sheet material usually falls with rise of temperature.

Recent tests upon a molded insulation with synthetic resin as the base or binder indicated a fall in transverse strength from 9500 lb. per sq. in. at 20 deg. C. to 4750 lb. per sq. in. at 100 deg. C., and a fall in compressive strength from 26,500 lb. per sq. in. at 20 deg. C. to 9000 lb. per sq. in. at 100 deg. C.

Low temperatures render most flexible or plastic insulating materials brittle and less resistant to impact, some much more than others. Even soft rubber may be chilled to a point when it can be powdered in a ball mill.

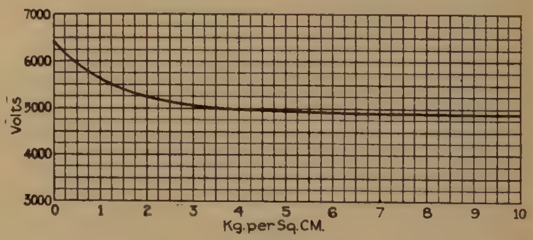


Fig. 9. Effect of Electrode Pressure Upon the Dielectric Strength of Presspahn

The effect of relative humidity upon the various physical properties of paper is shown in Fig. 11.†

Enough has been said to indicate the great difficulty of evaluating insulating materials from data usually available or furnished by manufacturers.

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*C. Kinzbrunner, *The Electrician*, 1905.

†These curves are taken from a paper entitled "The Effect of Atmospheric Humidity in the Physical Testing of Paper," by Messrs. Paul L. Houston, F. T. Carson, and R. S. Kirkwood, of the Bureau of Standards. This paper appeared in the *Paper Trade Journal*, April 12, 1923, and the curve is here reproduced by permission of the Director of the Bureau of Standards.

In the face of the conditions outlined, the following data were only a short time ago received from a correspondent in connection with a material in which he was interested:

> "The following facts are given regarding this material:
>
> Heat resistance, about 300 deg. C.
> Average insulating resistance, about 630,000 megohms per cm.
> Dielectric strength, about 1000-1100 volts per mm. thickness.
> Breaking strength, 250-350 kg. per cm.
> Water, acid, and weatherproof."

Just what does this information impart to a designer of electrical apparatus? Practically nothing.

It is obvious that many claims for insulating materials are quite valueless for the purpose of establishing a true relation between one or more materials. Furthermore, when definite values are claimed they are often so vague or unsupported by statements of testing conditions that the figures are of little use for purposes of calculation in the design of electrical apparatus. For instance, when the manufacturer of varnished cloth states that his material withstands 1000 volts per mil, just what does he mean? Certainly not that his material possesses this dielectric strength at all temperatures and humidities, in all thicknesses, and under all time conditions of voltage application. He can only mean that his material withstands 1000 volts per mil when tested under very definite conditions. If these conditions are not reported, there is no particular strength to the claim.

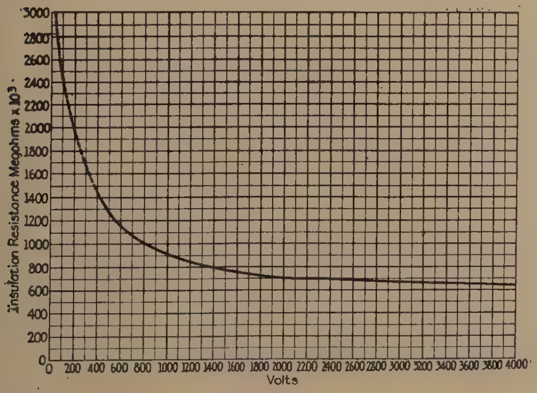

Fig. 10. Effect of Voltage Upon the Resistance of Wet Process Porcelain. Tests made on a tube $\frac{7}{16}$-in. inside diameter with $\frac{5}{32}$-in. wall

The ultimate solution of this complex question of course is the standardization of methods for testing insulating materials and for several years General Electric engineers concerned with the production and use of insulating materials have been engaged in formulating standard tests, working in conjunction with committees of the American Society for Testing Materials, the American Institute of Electrical Engineers, and other groups. The General Electric Company now has outlined over 80 standard tests for the various types of insulating materials. These tests cover the insulating or electrical properties and also the physical and chemical properties related to the performance of insulating materials under assembly and service conditions.

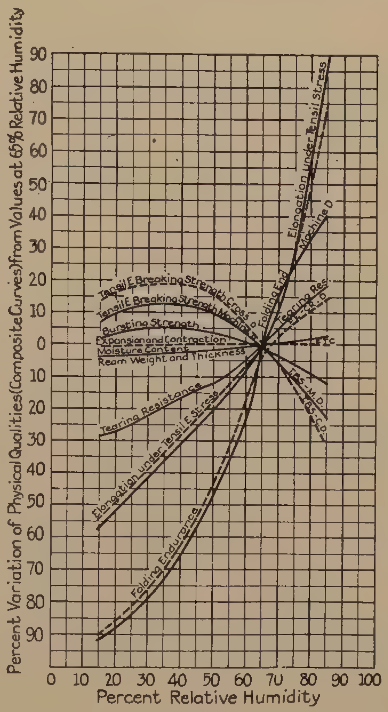

Fig. 11. Relative Variation of the Physical Qualities of Paper with Relative Humidity

With standard tests and standard specimens to be subjected to such tests, comparisons of insulations may be made much more reliably and test results may be much more safely utilized by electrical engineers.

Study of Crystal Structure and Its Applications

PART I

THE THEORY OF DIFFRACTION OF X-RAYS BY A CRYSTAL

By Wheeler P. Davey

Research Laboratory, General Electric Company

This is the opening installment of a series of articles that will develop into an up-to-date treatise on crystal structure as determined by x-rays and will become an invaluable guide to its diversified applications. Although this research was originated and developed by the scientist primarily for investigating the fundamental differences in the structural make-up of crystalline matter, the information so gained is almost every day leading to direct applications of this branch of crystallography to practical manufacturing problems, many of them in the field of metallurgy. To furnish a proper foundation for later installments, the phenomenon of x-ray diffraction by a crystal is treated in this issue under both the current theories "Diffraction of a Spreading Wave" and "Diffraction of a Quantum."—Editor.

Practically all rigid solids except the glasses and possibly certain waxes are composed of crystals. It is known to every metallurgist that metals and their alloys exist in the form of crystals, and the crystalline state of most chemical compounds is universally accepted. Even cellulose, of which wood and cotton are largely composed, shows some evidence of crystallinity. It is therefore evident that any study of the properties of materials will be very largely a study of the crystalline state of matter. There is the same difference between crystalline and non-crystalline substances that there is between an army and a mob, for a crystal represents an organized array of atoms all arranged in definite rows with regular spacings between rows, while the atoms in a non-crystalline substance have a chaotic, hit-and-miss placing.

It has long been known that the mechanical, optical, and chemical properties of crystals depend markedly upon the direction in the crystal in which these properties are measured. It was early taken for granted that this was caused by the various rows of atoms acting as units so that the effect of one atom was added to that of its neighbor in a perfectly systematic way. For a long time this picture was necessarily rather hazy, for no means were at hand to measure the distances between the atoms in the various rows and the distances between rows. These distances are so minute that if an ordinary pin head were magnified until its diameter became 100 miles, the distance between centers of adjacent atoms would be about one inch. Such measurements can now be made to within one part in a thousand by means of the diffraction of x-rays. In other words, x-rays furnish us with a micrometer by which we can measure distances of 10^{-8} cm. with an accuracy of one-tenth of one per cent.

A micrometer of this sort differs from an ordinary micrometer not only in the exceedingly small distances which it measures, but also in the fact that these distances lie hidden in the body of the crystal itself. As is the case with other micrometers, the measurement of a small distance is accomplished by measuring a relatively large distance (in this case, several centimeters) which is related to the desired distance by some known law. It will therefore be necessary to consider in detail the law of diffraction of x-rays and how this law may be made to relate large, easily measurable distances to the distances between atoms in crystals. In short, we must first study the theory of our micrometer. A study of the mathematics of crystal structure will then enable us to see how the interatomic distances may be used to determine the arrangement in space of the atoms of which a crystal is composed. From a knowledge of the structure of crystals it is possible to obtain information as to the sizes and shapes of atoms and ions, and to find valuable hints as to the mechanism of chemical combinations. Evidence is found leading to fundamental ideas in the theory of solid solutions and the inner structure of alloys, so that a more rational explanation may be made of certain metallurgical phenomena. Evidence may also be obtained of the effect of mechanical working on the orientation of crystals in metals so that we may hope some time in the future to roll and draw metal better than we can today. This short résumé shows that a study of crystal structure is not only of interest to the so-called "pure scientist" working in physics and chemistry, but that it gives much promise of practical results to the metallographer and through him to almost every branch of industry.

It was stated in the foregoing that the "micrometer" used in measuring interatomic distances is based upon the diffraction of x-rays. When x-rays of a given wavelength strike a substance, part of the radiation is scattered so that it appears at every possible angle to the incident beam. If the scattering substance is a crystal, the scattered radiation is much more intense at certain angles than at others; i.e., the x-rays are diffracted through definite angles. These angles depend upon the wavelength of the x-rays employed and upon the arrangement and spacing of the atoms in the crystal. The distance measured in determining these angles and the relative intensities of the x-ray beams at these angles form the basis of study in x-ray crystallography. The experimental fact of the diffraction of x-rays may be explained either on the basis of the classical spreading-wave theory,(1)(2) or on the basis of the quantum theory.(3) (4) A consideration of the two types of explanation shows that they give identical results.

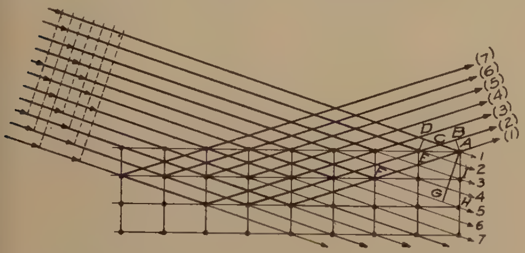

Fig. 1. **Diffraction of a Plane Wave by a Crystal**

Diffraction of a Spreading Wave

Let the network of dots in Fig. 1 represent the atoms of a crystal, and let the crystal receive x-rays from a source sufficiently distant so that the wavefronts may be considered to be planes. Let the arrows *1*, *2*, *3*, . . . represent normals to these wavefronts, and let the arrows (*1*), (*2*), (*3*) . . . represent the corresponding normals for the first order of the diffracted beam. Experimentally, it is found that the grazing angles of incidence and emergence are equal, i.e. that $DAE = BEA$. Let AG be drawn perpendicular to FH. Then $AFI = HFI$ and $FA = FH = FG + AH$ sin $GAH = FG + AH$ sin DAE. The path of the beam *5* to the point G is equal in length to the path of the beam *1* to the point A. The difference in path length between the beam *1* at A and the beam *5* diffracted from F to A is AH sin DAE. Since AH is twice the interplanar distance d of the crystal and DAE is the grazing angle θ, we know the waves diffracted along (*1*) from incident beams *1* and *5* will meet in phase if

$$n\,\lambda = 2\,d \sin\theta \qquad (1)$$

where n is any whole number and λ is the wavelength of the x-rays employed. The integer represented by n is called the "order" of diffraction. Similar beams such as (*2*), (*3*), (*4*), . . . will be in phase with beam (*1*); for let ED and AB be perpendicular respectively to *1* and (*1*). Then since $BEA = DAE$ the path $EC + CB$ equals the path $DC + CA$.

It is therefore possible to have a whole wavefront of diffracted x-rays emerging from a crystal at an angle equal to the angle of incidence provided this angle is related to the wavelength of the x-rays and the interplanar distance of the crystal in the manner shown by equation (1). It may be shown that if the crystal were infinitely thick and offered no absorption to the x-rays, there could be no first-order diffracted beam at any other angle; for no matter what other angle we choose for diffraction from a given point in the crystal, there will be some other point which can send out a wave in the same direction which will meet the first a half wavelength out of phase. Experimentally, it is found that it is sufficient if the crystal is about 10^5 atoms (10^{-3} cm.) thick. If the crystals are too thin, the diffracted beam tends to widen because of incomplete interference at angles other than that which is equal to the angle of incidence.

The diffraction of x-rays by a crystal may be shown analytically as follows. The three-dimensional diffraction grating of a crystal may be regarded as composed of three sets of uni-dimensional gratings, each one of which consists of a row of atoms parallel to one of the three axes of the crystal. Let the interatomic distances along the three axes be x_1, y_1, and z_1. Let the directions of the incident and diffracted beams be expressed by their direction cosines α_1, β_1, γ_1 and α_2, β_2, γ_2 respectively. Then the conditions for refraction along these three sets of linear gratings are

$$\left.\begin{aligned} x_1\,(\alpha_2 - \alpha_1) &= e\,\lambda \\ y_1\,(\beta_2 - \beta_1) &= f\,\lambda \\ z_1\,(\gamma_2 - \gamma_1) &= g\,\lambda \end{aligned}\right\} \qquad (2)$$

where e, f, and g are integers representing the order of the diffracted beam from each of the gratings. In the simplest case, that of a cubic crystal $x_1=y_1=z_1=d$ the side of the unit cube. Remembering that

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(1) X-Rays and Crystal Structure, Chap. II.
W. H. and W. L. Bragg. (Bell and Sons, London 1915).

(2) Kristalle und Roentgenstrahlen.
P. P. Ewald. (Julius Springer, Berlin 1923).

(3) Wm. Duane, *Proc. Nat. Acad. Sci.*, *9*, 158 (1923).

(4) A. H. Compton, *Proc. Nat. Acad. Sci.*, *9*, 359 (1923).

$$\alpha^2_1+\beta^2_1+\gamma^2_1=\alpha^2_2+\beta^2_2+\gamma^2_2=1$$

we have by squaring and adding

$$2-2(\alpha_1\,\alpha_2+\beta_1\,\beta_2+\gamma_1\,\gamma_2)=\left(\frac{\lambda}{x_1}\right)^2(e^2+f^2+g^2)$$

But since, by a well-known theorem in trigonometry

$$\alpha_1\,\alpha_2+\beta_1\,\beta_2+\gamma_1\,\gamma_2=\cos\phi$$

where ϕ is the angle between the incident and the diffracted beams, and since $2\,(1-\cos\phi)=4\sin^2\frac{\phi}{2}$ we have

$$2\sin\frac{\phi}{2}=\frac{\lambda}{x_1}\sqrt{e^2+f^2+g^2} \qquad (3)$$

We may therefore calculate the angle of deviation ϕ from the wavelength λ, the grating space x_1, and the orders of the diffraction patterns of the three sets of linear gratings.

Equation (3), derived in this way, may be regarded as typical of the viewpoint of Laue at the time of his discovery of x-ray diffraction. It may be expressed in terms of the more useful Bragg viewpoint as follows: A plane of atoms in a crystal is most commonly defined by its "Miller indices," which are the reciprocals of the intercepts of the plane upon the x, y, and z-axes respectively. For instance, the *1 0 0* plane cuts the x-axis at unit distance, and is parallel to the other two axes; it is the side of a cube or of some other orthogonal figure. The *3 2 1* plane cuts the x-axis at ⅓, the y-axis at ½, and the z-axis at unity. (In this connection see any standard book on Crystallography.) It is customary to express these reciprocal intercepts in terms of their lowest prime numbers, so that if the intercepts are given as *h k l*, the actual reciprocal intercepts will be *nh*, *nk*, and *nl*, where *n* is any integer. If, therefore, we choose such a plane of atoms that

$$e=nh$$
$$f=nk$$
$$g=nl$$

we may regard the diffracted beam of equation (3) to be a diffracted beam of the *n*th order from the plane *h k l*. Equation (3) may therefore be written

$$2\sin\frac{\phi}{2}=\frac{\lambda}{x}\,n\sqrt{h^2+k^2+l^2}$$

or

$$n\lambda=2\left(\frac{x}{\sqrt{h^2+k^2+l^2}}\right)\sin\frac{\phi}{2} \qquad (4)$$

But $\frac{x}{\sqrt{h^2+k^2+l^2}}$ is the distance between successive *h k l* planes. It is the *d* of equation (1).

The grazing angle of incidence (or the angle of diffraction) is $\frac{\phi}{2}$ and is the θ of equation (1). It is therefore evident that equations (4) and (1) are identical. If instead of confining ourselves to the cubic system, we had taken any other crystal system, we would have arrived at an expression inside the parenthesis of equation (4) which would represent the distance *d* between successive planes for that crystal system.

Diffraction of a Quantum

In the preceding section on "Diffraction of a spreading wave" we have regarded an x-ray as a train of spherical waves of short wavelength spreading out from a point source. The picture of an x-ray from the standpoint of the quantum theory may be given sufficiently well for our present purpose by regarding it as a wavetrain of very small cross-section (possibly of the order of 10^{-25} sq. cm.) proceeding out in a straight line from its source.(5) Any x-ray beam with which we ordinarily deal is supposed to contain an enormous number of these quanta coming out in all directions from the "focal spot" on the anode of an x-ray tube. In many ways the whole bundle of quanta acts much like a train of spreading spherical waves, but the mechanism by which diffraction must be explained is quite different for quanta than it is for spreading spherical waves.

According to the quantum theory, it is a characteristic of a quantum that its energy, *E*, determines the frequency of its waves, i.e.

$$E=h\nu=\frac{hc}{\lambda} \qquad (5)$$

where ν is the frequency, λ the wavelength, *c* the velocity of light, and *h* is a proportionality constant known as "Planck's constant." If for any reason a quantum loses a portion of its energy it must decrease the frequency of its waves until the new frequency multiplied by Planck's constant gives a product equal to the energy still remaining in the quantum. Since the wave has energy and has a definite velocity, *c*, it may be said (at least figuratively) to have mass and therefore momentum. It may be shown that the momentum of a quantum is

$$\mathbf{M}=\frac{h\nu}{c}=\frac{h}{\lambda} \qquad (6)$$

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(5) W. P. Davey, *Jour. Frank. Inst.*, *197*, 478, 629 (1923).

The ordinary law of conservation of momentum which holds for the impact of material bodies is assumed to hold for the impact of quanta on atoms and electrons. It is further assumed that a quantum can give up momentum to an atom or electron in definite units. Since h has the dimensions of a momentum multiplied by a length, it is assumed that the quantum-unit of momentum is $\frac{h}{l}$ where l is any length which may be shown to have a physical meaning.

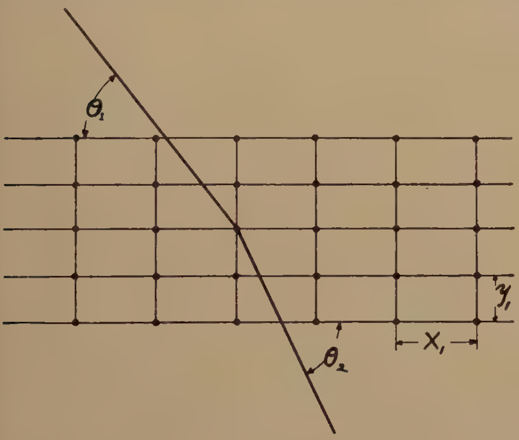

Fig. 2. Diffraction of a Quantum by a Crystal

Let a quantum of x-rays fall upon a crystal as shown in Fig. 2 so as to make a grazing angle θ_1. At some point in its path it may hit an electron belonging to one of the atoms of the crystal and be deflected so that it emerges at an angle θ_2. The momentum transferred to the crystal in a direction parallel to the x-axis is

$$\frac{h\nu}{c}(\cos\theta_1-\cos\theta_2)=n_1\frac{h}{x_1} \qquad (7)$$

where the interatomic distance x_1 is the only length in the x-direction which has any physical meaning, and where n_1 is any positive integer including zero. Similarly, the momentum transferred in the y-direction is

$$\frac{h\nu}{c}(\sin\theta_1-\sin\theta_2)=n_2\frac{h}{y_1} \qquad (8)$$

If n_1 and n_2 are both zero, there is no transfer of momentum and no change in direction, so that the quantum passes on through until it hits an electron in some other atom. If n_1 is zero and n_2 is not zero, then $\cos\theta_1=\cos\theta_2$ but $\sin\theta_1$ does not equal $\sin\theta_2$, so that $\theta_1=-\theta_2$. Equation (8) therefore becomes

$$\frac{2h\nu}{c}\sin\theta_1=n_2\frac{h}{y_1} \qquad (9)$$

or

$$n_2\lambda=2y_1\sin\theta_1 \qquad (10)$$

which is identical with equation (1) for diffraction from the xz-planes. Similarly if n_2 is zero but n_1 is not zero,

$$n_1\lambda=2x_1\sin\theta_1 \qquad (11)$$

which represents diffraction from the yz-planes. Equations (10) and (11) may therefore be written in the form of equation (1)

$$n\lambda=2\,d\sin\theta \qquad (1)$$

If n_1 and n_2 are both integers other than zero, equations (7) and (8) give the same law of diffraction for still other families of planes in the crystal.

Primary and Secondary Standards for the Determination of d in Equation (1)

Equation (1) gives the relation between the wavelength of x-rays and the interplanar spacing for diffraction at a given grazing angle. In order to determine either of these quantities by means of this equation it is necessary to know the other. Using the method of W.H. and W.L. Bragg[6] we may determine the dimensions of the unit crystal of Na Cl as follows: A study of the diffraction patterns of Na Cl and K Cl shows that these patterns may be accounted for if these salts crystallize as simple cubes of ions, with the alkali and halogen ions occupying alternate corners of the cubes. Since this is the simplest structure which accounts for the experimental facts, it will be adopted as the structure of Na Cl. Each corner of one of the elementary cubes (unit-cubes) of the crystal contributes ⅛ atom to the cube. The mass of the unit cube of Na Cl is therefore $\frac{1}{2}[A_{Na}+A_{Cl}]\,m$ where

A_{Na} is the atomic weight of Na = 23.000
A_{Cl} is the atomic weight of Cl = 35.458
m is the mass in grams associated with one unit of atomic weight.

The factor m is most easily found as e/F where e is the charge on the electron and F is the Faraday constant in electrolysis. Millikan[7] gives e as 4.774×10^{-10} abs. e.s. units of charge or 1.591×10^{-19} absolute coulombs. The maximum error is about 0.1 per cent. Vinal and Bates[8] give F as 96,500 absolute coulombs with a maximum error of 0.01 per cent. The factor m is therefore 1.649×10^{-24} grams. This makes the mass of the unit cube of

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(6) W. H. and W. L. Bragg, *Proc. Roy. Soc.*, *88*, 428 (1913).
(7) R. A. Millikan, *Proc. Nat. Acad. Sci.*, *3*, 314 (1917).
(8) Vinal and Bates, *Bull. Bureau of Standards*, *10*, 425 (1914).

Na Cl 4.820×10^{-23} grams. Baxter and Wallace,(9) using great care to obtain pure salt, have measured the density of Na Cl as 2.161. The volume of the unit cube of Na Cl is therefore 22.303×10^{-24} c.c. and the side is $a = 2.815 \times 10^{-8}$ cm. If the density is correct to within 0.003, this value for the side of the unit cube of Na Cl should be correct to within 0.001×10^{-8} cm.

The density of calcite can be measured with greater accuracy than the density of Na Cl. For this reason the side of the unit rhombohedron of calcite is taken as a primary standard and the side of the unit cube of Na Cl is determined from this as a secondary standard.(10) Duane gives(11) $a_{CaCO_3} = 3.028 \times 10^{-8}$ cm. and $a_{NaCl} = 2.814 \times 10^{-8}$ cm. These standard values differ but little from those proposed by McKeehan.(12) Wavelengths of x-rays determined from equation (1) with the aid of these values for a agree with the results of calculations based on the quantum theory.(12) This is perhaps the best justification for adopting the simple interpretation just given for the diffraction pattern of Na Cl.

Exceptions to the Simple Form of Bragg's Law

Equation (1) does not correlate all the known facts on the diffraction of x-rays. It is therefore necessary to extend the simple theories on which equations (1), (10), and (11) were founded. These extensions introduce the ideas of refractive index and of extraordinary diffraction.

It is found experimentally that for a given crystal, equation (1) gives slightly higher values for wavelengths when n is small (1 or 2) than when n is larger. In the same way, if the wavelength is assumed to be known, the first few lines in the diffraction pattern appear to be caused by an interplanar spacing in the crystal which is slightly larger than that calculated from the second order of these same lines. This effect is explained as being caused by certain electrons in the atom having natural periods of vibration close to that of the incident beam of x-rays, thus giving the effect of a refractive index less than unity.(13) Davis and von Nardroff(14) have determined the refractive index of pyrites for four wavelengths and have compared their results with calculations based on Lorenz' dispersion formula

$$1-\mu=\frac{e^2}{2\pi m}\left(\frac{n_1}{\nu^2-\nu_1^2}+\frac{n_2}{\nu^2-\nu_2^2}+\ldots\right)$$

where μ is the index of refraction, ν is the frequency of the incident beam, and n_1, n_2, . . . are the number of electrons per unit volume having natural frequencies ν_1, ν_2, . . . Their calculated and experimental values are compared in Table I. When the planes of atoms from which the rays are diffracted are parallel to the surface of the crystal (as is the case when a cleavage face is used) the error caused by refraction is very small. For instance, the bending is only about three seconds of arc for the K_α rays of Mo from a cleavage face of calcite. This bending increases as the angle between the atomic planes and the crystal surface is increased. It is greater the shorter the wavelength of x-rays employed. This is illustrated by the data of Table II from Davis and von Nardroff for pyrites.

TABLE I

Index of Refraction of Pyrites Crystal for X-rays

λ	$1-\mu$ Experimental	$1-\mu$ Calculated
0.6311A	2.82×10^{-6}	2.62×10^{-6}
0.7078	3.33×10^{-6}	3.29×10^{-6}
1.389	13.2×10^{-6}	13.5×10^{-6}
1.537	17.6×10^{-6}	17.6×10^{-6}

In certain experiments on x-ray diffraction, a crystal is mounted in the path of the x-ray beam so that the x-rays just graze some one of its faces. The crystal-mounting is so arranged that the crystal may be rotated about an axis which passes through this face and through the x-ray beam and which is perpendicular to the direction of the beam. A suitable detecting instrument, such as an ionization chamber, is also arranged so that it can be rotated about this same axis. If the crystal face is now rotated to make an angle θ with the beam, and the ionization chamber makes an angle 2θ, then the wavelength of x-rays from the primary beam which will be deflected into the ionization chamber will depend only upon the angle θ and the grating space of the crystal face in accordance with equation (1). This method is commonly used to determine the distribution of intensity for different wavelengths in the spectrum of an x-ray tube. If, however, the primary beam contains wavelengths which are capable of exciting "characteristic" x-rays from the atoms of the crystal, Clark and Duane find(15) (16) that in addition to the spectrum of the target material of the x-ray tube, an "extraordinary" spectrum of the characteristic rays is obtained superimposed upon the first. The effect is the same as if the target material of the x-ray tube contained some atoms like those in the crystal except that the relative intensities of the lines are different. This "extraordinary" beam obeys all the principles of diffraction as expressed in equation (1) if we assume that the angle of incidence of the characteristic rays is the same as that of the primary beam. This assumption involves some interesting speculations on the methods by which characteristic rays are produced in a crystal. Further experimental work may lead to definite ideas in this connection.

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(9) Baxter and Wallace, *Jour. Am. Chem. Soc.*, *38*, 260 (1916)

(10) M. Siegbahn, *Phil. Mag.*, *37*, 601 (1919).

(11) Wm. Duane, *Bul. Nat. Res. Coun.*, No. 6 (1920).

(12) L. W. McKeehan, *Science*, *56*, 757 (1922).

(13) C. G. Darwin, *Phil. Mag.*, *27*, 318 (1914)
W. Stentrom, *Doctor's Dissertation*, Lund (1919).
E. Hjalmar, *Zeit. Phys.*, *7*, 341 (1921).
Davis and Terrill, *Proc. Nat. Acad. Sci.*, *8*, 357 (1922).

(14) Davis and von Nardroff, *Proc. Nat. Acad. Sci.*, *10*, 60 (1924) and in private communication.

(15) Clark and Duane, *Proc. Nat. Acad. Sci.*, *8*, 90 (1922).

(16) L. W. McKeehan, *Jour. Opt. Soc. Am.*, *6*, 989 (1922).

TABLE II

Effect of Angle and Wavelength on the Index of Refraction of Pyrites for X-rays

λ	Angle between crystal surface and atomic planes	Angle of bending of x-rays	$(1-\mu)$	Weighted mean $(1-\mu)$
0.7078A	0° 0′ 0″	3.6″	4.6×10^{-6}	
	6° 31′ 57.5″	39″	3.26×10^{-6}	
	7° 18′ 39″	159″	3.37×10^{-6}	3.33×10^{-6}
0.6311A	0° 0′ 0″	3″	3.87×10^{-6}	
	6° 31′57.5″	160″	2.82×10^{-6}	2.82×10^{-6}

Extraordinary diffraction of this sort will be called hereafter "Characteristic Diffraction" to distinguish it from a second sort of extraordinary diffraction about to be described.

If, instead of rotating both the crystal and the ionization chamber, the crystal is fixed at some convenient angle and the ionization chamber is rotated alone, then, if no characteristic rays are produced in the crystal, diffracted beams of x-rays will be found corresponding to the various orders of diffraction of some one wavelength in the primary beam. This wavelength may be calculated from the grazing angle of the primary beam on the crystal face, and the grating space of the crystal by means of equation (1). But if "characteristic" x-rays are excited in the crystal an additional diffracted beam will be found symmetrically placed on each side of the "ordinary" diffracted beam. This type of "extraordinary diffraction" will be called "Anomalous Diffraction." It seems to be caused by rays which are characteristic of the atoms in the crystal, for it occurs only when the characteristic rays are excited. The angle of incidence does not equal the angle of diffraction, and equation (1) is not obeyed.

Explanation of Characteristic Diffraction

It has already been stated that characteristic diffraction obeys equation (1) if it is assumed that the angle of incidence of the characteristic rays is the same as that of the primary beam. In explaining this effect, the quantum theory has the advantage over the spherical-wave theory in that it provides a mechanism by which this can take place.

Experimentally, extraordinary diffraction never occurs by itself. The ordinary diffraction pattern always accompanies it. This makes it seem plausible that some wavetrains find the atoms in the crystal in a state favorable for the production of characteristic x-rays and so produce extraordinary diffraction, while others find the atoms in some less favorable state and so are diffracted in the ordinary way. Such a view is consistent with the conceptions underlying the quantum theory of radiation. It is not surprising therefore that the phenomena of characteristic diffraction can be explained on the basis of Duane's quantum theory of diffraction.(17)

In the discussion of the simple form of the quantum theory on page 745, it was assumed that all transfers of momentum from x-rays to electrons were in exact multiples of a "quantum of momentum" $\frac{h}{l}$ in which h is Planck's constant and l is some length to which may be attached a physical meaning. If, however, these transfers of momentum are not exact multiples of the "quantum of momentum," the x-rays must lose energy in some way until only exact multiples of the quantum of momentum are available for transfer to the electrons in the atoms of the crystal. This loss may appear in various ways. If the wavelength of the primary beam is slightly less than the shortest wavelength of some group of x-rays which is characteristic of some atom in the crystal,(18) the loss in energy from the primary beam will appear largely in the form of "characteristic x-rays." Let the energy of the incident quantum be ϵ and let ϵ' be that portion of ϵ which appears as characteristic x-rays. Then $\epsilon' = \epsilon_1 + \epsilon_2 + \epsilon_3 + \ldots$ where ϵ_1 etc. represent the energy in each of the wavelengths represented in the characteristic spectrum. If α_1, β_1, γ_1, are as before the direction cosines of the primary beam and α_2, β_2, γ_2, the direction cosines of the emerging characteristic rays, then equation (7) becomes

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(17) Wm. Duane, *Proc. Nat. Acad. Sci.*, *9*, 158 (1923).

$$\left.\begin{aligned} \alpha_1\frac{\epsilon}{c} - \alpha_2\frac{\epsilon'}{c} &= MV_x + mv_x + n_1\frac{h}{x_1} \\ \beta_1\frac{\epsilon}{c} - \beta_2\frac{\epsilon'}{c} &= MV_y + mv_y + n_2\frac{h}{y_1} \\ \gamma_1\frac{\epsilon}{c} - \gamma_2\frac{\epsilon'}{c} &= MV_z + mv_z + n_3\frac{h}{z_1} \end{aligned}\right\} \quad (12)$$

where M and m are the masses and V and v the velocities of the atom and electron respectively and c is the velocity of light.

If, now, we assume that the portion of the momentum of the incident quantum which is imparted to the atom as a whole and to some electron in the atom is transferred without any change in direction,

$$\left.\begin{aligned} (\epsilon/_c - \epsilon'/_c)\ \alpha_1 &= MV_x + mv_x \\ (\epsilon/_c - \epsilon'/_c)\ \beta_1 &= MV_y + mv_y \\ (\epsilon/_c - \epsilon'/_c)\ \gamma_1 &= MV_z + mv_z \end{aligned}\right\} \quad (13)$$

Subtracting equation (13) from (12) we have

$$\left.\begin{aligned} \frac{\Sigma\,(e_1)}{c}(\alpha_1 - \alpha_2) &= n_1\frac{h}{x_1} \\ \frac{\Sigma\,(e_1)}{c}(\beta_1 - \beta_2) &= n_2\frac{h}{y_1} \\ \frac{\Sigma\,(e_1)}{c}(\gamma_1 - \gamma_2) &= n_3\frac{h}{z_1} \end{aligned}\right\} \quad (14)$$

The left-hand side of each equation (14) contains as many terms as there are separate lines in the characteristic spectrum under consideration. A sufficiently close approximation may be obtained in the K series by using only the K_γ line. This leads to the approximate equations.

$$\left.\begin{aligned} \frac{e_1}{c}(\alpha_1 - \alpha_2) &= n_1\frac{h}{x_1} \\ \frac{e_1}{c}(\beta_1 - \beta_2) &= n_2\frac{h}{y_1} \\ \frac{e_1}{c}(\gamma_1 - \gamma_2) &= n_3\frac{h}{z_1} \end{aligned}\right\} \quad (15)$$

In accordance with the principles of the quantum theory, the quantum must assume such a wavelength that

$\epsilon_{K_\gamma} = h\nu_{K_\gamma} = h\frac{c}{\lambda_{K_\gamma}}$. Equations (16) may therefore be written,.

$$\left.\begin{aligned} x_1\ (\alpha_1 - \alpha_2) &= n_1\lambda_{K_\gamma} \\ y_1\ (\beta_1 - \beta_2) &= n_2\lambda_{K_\gamma} \\ z_1\ (\gamma_1 - \gamma_2) &= n_3\lambda_{K_\gamma} \end{aligned}\right\} \quad (16)$$

These equations state that in extraordinary diffraction of the first type the characteristic radiations come off from the crystal in directions approximating those directions which obey the laws of ordinary diffraction by a crystal if we remember that the wavelength is different from that in ordinary diffraction. "In spectra of higher orders the direction cosines have higher values than in the spectra of lower orders and on this account we would expect somewhat more sharply marked reflections(19) in the former than in the latter."(17)

As far as is known to the writer, the problem of anomalous diffraction has not been solved. A suggestion for its solution made by McKeehan(16) is stated by him in private correspondence not to be in quantitative agreement with the data which have since been published.

Characteristic diffraction has been made the basis of a very powerful method of crystal analysis by Clark and Duane.(15) (20) (21) A detailed consideration of the method will be postponed, however, until after taking up methods based upon the laws of ordinary diffraction.

(*To be continued*)

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(18) These values are tabulated in "Data relating to x-ray spectra" by Wm. Duane, *Bul. Nat. Res. Council*, Vol. 1, No. 6 (1920).

(19) Since the grazing angle of incidence and the corresponding angle of diffraction are equal in the case of ordinary diffraction, the word "reflection" is often used in the literature in a broad way instead of the strictly accurate word "diffraction."

(20) Clark and Duane, *Proc. Nat. Acad. Sci.*, *9*, 117, 126, 131, 398 (1923). *Jour. Opt. Soc. Am.*, *7*, 455 (1923). *Science*, *58*, 398 (1923).

(21) G. L. Clark, *Jour. Am. Chem. Soc.*, *46*, 372 (1924).

Studies in the Projection of Light

PART XIV

SURFACE ERRORS IN SECOND-SURFACE MIRRORS

By FRANK BENFORD

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In this installment the author discusses the influence of manufacturing errors on the projection of light from a paraboloidal mirror. The data and equations may after simple transformation be used for plane, ellipsoidal, and hyperbolic second-surface mirrors as well as for parabolic mirrors, and the treatment is thus applicable to second-surface mirrors in general. It is shown that the second or silvered surface is of much greater importance than the first surface when we consider the results of grinding errors upon the beam intensity. In every day practice, it is customary to focus each mirror, either by "eye" or by some more complicated photometric process, but whatever method is employed, the final result is a compromise between two beams from the two surfaces. The author accordingly points out that this compromise can be made the basis of estimating the relative importance of the two surfaces. Any extended discussion of mirrors is certain to bring up the subject of glare from the automobile headlight, and it is shown that if either surface is optically defective the beam will glare due to the presence of a zone of stray light around the main beam, and escape from this glare is not possible by any adjustment of the source of light.—EDITOR.

Regardless of the rectitude of intentions and the honesty of workmanship, there is always in the best of work something still to be desired. In such an object as a mirror used for the projection of light, the ease of mathematical treatment is an incentive to study the results of the inevitable optical defects in the mirror. The reflectors in which we are interested are in some ways products of engineering rather than science, for the scientific eye is single to the laws of Nature which, for reasons unknown, do not seem to include finance and the feeble and uncertain efforts of our heads and hands. As engineers, we should give graphs and equations showing how the optical errors are related to the price and how many million candles can be added for each day expended in the grinding. Here the engineering problem becomes too difficult, and we can only make the familiar retreat to the realm of pure science and find out how things act when they are not exactly what they ought to be. Every advanced engineering branch has somewhere a twig called its "Theory of Errors," and in the following pages some of the simpler and more fundamental errors in the paraboloidal mirror are outlined. The information so gained has several direct applications in daily life and can be related to some of the observations in personal experience.

Nature of Surface Errors

The optical errors in a mirror of good quality are practically all in the meridian plane. In the language of the shop the mirrors show "zones." The variations in thickness around any concentric circle are extremely small, and therefore attention may be confined to the surface variation along a meridian. The results will show not only the zones that result from the manufacturing process, but also the variations that originate in the design. The data given later show how a given surface error influences the projected beam, and they also illustrate both the relative sensitiveness of the two surfaces and the sensitiveness of various parts of the same surface.

The derivation of equations is made for the particular case of the paraboloid, largely because this surface is much the simplest of the conics, but the curves and equations may be directly applied to the plane mirror, the ellipsoid, or the hyperboloid as well as the paraboloid. The equations are in terms of the angles of incidence and refraction at the surface point under investigation, and the resultant error of projection is independent of the curvature of any other section of the mirror, that is, independent of its general form.

It might be mentioned that in the analysis immediately following no attention is paid to the independent beam from the front surface, but this should not give rise to the inference that the front surface beam is not of importance.

Nomenclature:

Let S_1 (as shown in Fig. 150) indicate the surface at the point of incidence of a ray from the focal point.

V_1 be the angular error in direction of this surface, measured in a meridian plane at S_1.

i be the angle of incidence, measured from the normal.

r be the angle of refraction, measured from the normal.
n be the refractive index, equal to 1.52.
de_1 be the error in direction of the refracted ray at S_1.
de_2 be the error in the direction of the reflected ray at S_2, etc.
a be the generating angle of the parabolic front surface.
p be the length of the radius vector from the focal point to S_1.
E_1 be the final error of projection due to the angular error V_1 at S_1.

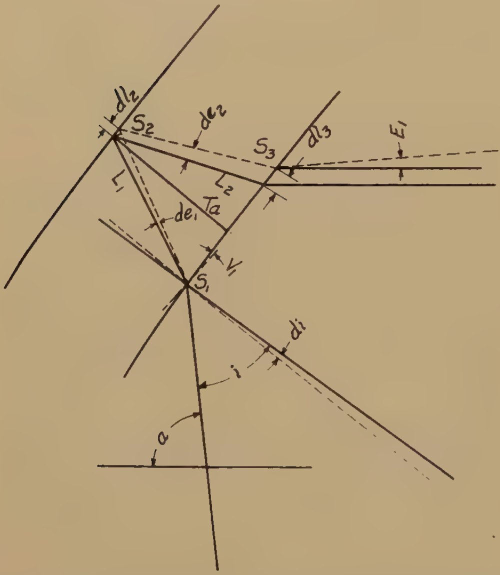

Fig. 150. The solid lines in the diagram indicate the path of a correctly refracted ray, while the dotted lines indicate the path taken by a ray refracted from the correct path by a surface error V_1 at the point S_1. The original error is modified by the ray shifting to a new point of reflection at S_2 on the second surface and to a new point of refraction at S_3 on the first surface

CASE I: *Let the first surface at S_1 be in error by angle V_1 in the meridian plane. The surfaces at S_2 and S_3 (see Fig. 150) are correct in direction.*

By Snell's law

$$\sin i = n \sin r \qquad (176)$$

and differentiating

$$\cos i \, di = n \cos r \, dr \qquad (177)$$

Therefore we have the two useful expressions

$$di = \frac{n \cos r}{\cos i} dr \qquad (178)$$

and

$$dr = \frac{\cos i}{n \cos r} di \qquad (179)$$

both of which equations will be used later.

The differential coefficient

$$\frac{di}{dr} = \frac{n \cos r}{\cos i} \qquad (180)$$

is of great importance in forming a mental picture of what takes place when a refracted ray varies slightly in its position relative to the normal. In Fig. 152 the values of $\frac{di}{dr}$ and $\frac{dr}{di}$ are plotted for various angles of incidence. At near normal incidence a variation from the correct or original direction of say 1 min. in the incident ray will produce a variation of 0.66 min. in the refracted ray. At 70 deg. incidence the same variation will produce only 0.285 min. change in the direction of the refracted ray. If the ray is emerging from the glass at an air angle of 70 deg., a change of 1 min. before refraction will produce 3.50 min. in the direction of the air path. The influence of this great multiplication will be taken up later.

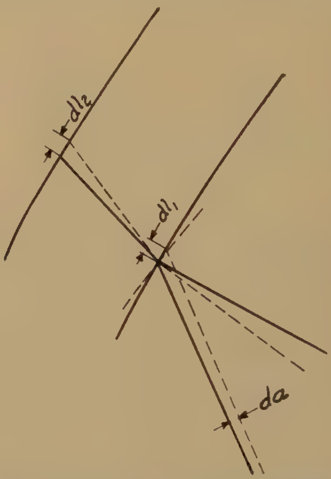

Fig. 151. The curvature of the co-paraboloid or second surface has not been determined, but in this diagram it is assumed to be equal to the curvature of the first surface, so that dl_2 is identical in all respects to dl_1

Returning to the surface in error at S_1, Fig. 150, the surface error being V_1, the normal will be also turned through the angle V_1, and the angle of incidence i_1 becomes, for a clockwise or positive value of V_1

$$i_1 = i - V_1$$

or

$$V_1 = i - i_1 \qquad (181)$$

As V_1 is a small angle we may write

$$V_1 = di_1 \qquad (182)$$

and the corresponding change between normal and ray in the glass is, from equation (179),

$$dr_1 = \frac{\cos i}{n \cos r}\, di_1 \qquad (183)$$

But the normal itself has moved through an angle V_1, and the net movement in space of the ray in the glass is

$$\begin{aligned} de_1 &= V_1 - dr_1 \\ &= di_1 - dr_1 \\ &= \left(\frac{n \cos r - 1}{\cos i}\right) dr_1 \qquad (184) \end{aligned}$$

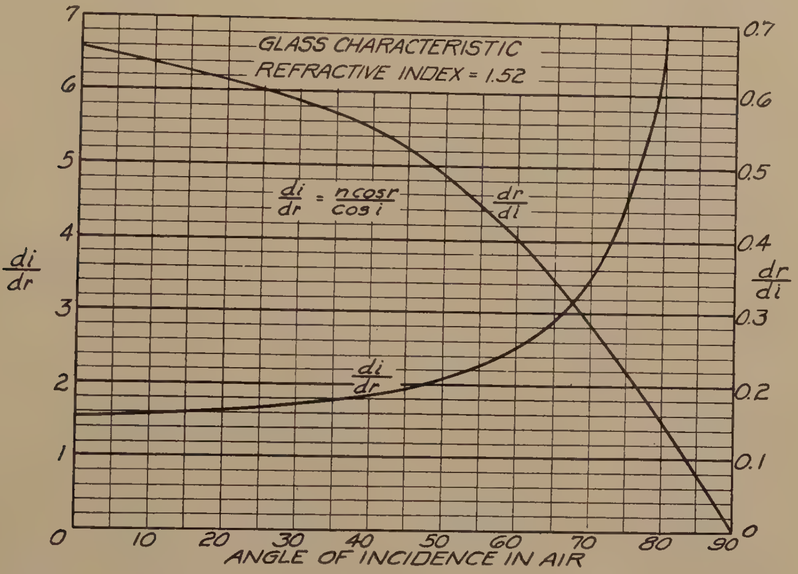

Fig. 152. The rate of change of the internal angle as compared with the external angle is illustrated by the curve marked $\frac{dr}{di}$ and the reciprocal rate by the curve marked $\frac{di}{dr}$. The multiplication of directional errors when a ray leaves glass at a large angle to the normal is one of the factors that put a limit to the depth of the paraboloidal second-surface mirror that can be economically built

and also, from equation (183), we have the alternate form

$$de_1 = \left(1 - \frac{\cos i}{n \cos r}\right) di_1 \qquad (185)$$

This error in direction de_1 will remain unchanged in magnitude upon reflection (although reversed in sign) at the second surface, but a new error will be introduced due to the ray being shifted a distance dl_2 along the silvered surface. To find the magnitude of this error due to the displacement of the reflection point of the ray, let us measure the distance dl_2 in terms of the original angle of incidence i.

The physical length of path from S_1 to S_2 is found as follows (in a similar manner to the optical length):*

$$L = \frac{T_a}{\cos r} \qquad (186)$$

but

$$T_a = \frac{T_o}{\cos r} \qquad (187)$$

therefore

$$L = \frac{T_o}{\cos^2 r} \qquad (188)$$

and

$$\begin{aligned} dl_2 &= \frac{L}{\cos r}\, dr_1 \\ &= \frac{T_o}{\cos^3 r}\, dr_1 \qquad (189) \end{aligned}$$

If the same distance dl_2 is laid out on the first surface as dl_1 upward from S_1 as in Fig. 151, we have in terms of a and p

$$dl_1 = \frac{p\, da}{\cos \frac{a}{2}} \qquad (190)$$

but

$$\frac{a}{2} = i \qquad (191)$$

and

$$da = 2\, di \qquad (192)$$

also

$$p = \sec^2 \frac{a}{2} \qquad (193)$$

therefore

$$dl_1 = \frac{2\, di}{\cos^3 i} \qquad (194)$$

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*Part XII, General Electric Review, Sept., 1924, p. 630.

and

$$\begin{aligned} di &= \tfrac{1}{2}\cos^3 i\, dl_1 \\ &= \frac{T_0 \cos^3 i}{2\cos^3 r}\, dr_1 \end{aligned} \qquad (195)$$

We may here safely assume that the rear surface changes direction by the same angle as the front surface in the common distance dl_2, and therefore equation (195) shows that the slope of the rear surface in the distance dl_2 changes direction by an amount di between the original and the new point of incidence of the improperly refracted ray. The reflected ray will be turned through twice the angle through which the normal and the mirror surface turns, therefore the error due to displacement is

$$de_2' = \frac{T_0 \cos^3 i}{\cos^3 r}\, dr_1 \qquad (196)$$

The error de_1 at the point of entrance S_1 is reversed in sign upon reflection, but is unchanged in value. The total error in direction upon leaving S_2 is therefore

$$\begin{aligned} de_2 &= de_1 - de_2' \\ &= \left[\left(\frac{n\cos r}{\cos i} - 1\right) - \frac{T_0 \cos^3 i}{\cos^3 r}\right] dr_1 \end{aligned} \qquad (197)$$

Upon incidence at S_3 another displacement dl_3 is introduced

$$dl_3 = dl_2\left(1 + \frac{de_2'}{de_1}\right) \qquad (198)$$

and this involves a rotation of the normal at S_3 between the correct and incorrect points given by equation (199).

$$\begin{aligned} de_2' &= \left[1 + \frac{\left(\frac{n\cos r}{\cos i} - 1\right) dr_1 - \frac{T_0\cos^3 i}{\cos^3 r}\, dr_1}{\left(\frac{n\cos r}{\cos i} - 1\right) dr_1}\right] \frac{T_0 \cos^3 i}{\cos^3 r}\, dr_1 \\ &= 2\left[1 - \frac{\cos^3 i}{2\left(\frac{n\cos r}{\cos i} - 1\right)\cos^3 r}\, T_0\right] \frac{T_0\cos^3 i}{\cos^3 r}\, dr_1 \end{aligned} \qquad (199)$$

The term to the right in the bracket is ordinarily small in comparison with unity. Thus for the mirror we have been using for illustrating the computations, this term amounts to 0.035 at zero degrees, 0.02 at 60 deg., and if the mirror were extended to 120 deg. the term would be only 0.003. Therefore, unless for some reason highly accurate data are desired we may use the simple form

$$de_3' = \frac{2\, T_0 \cos^3 i}{\cos^3 r}\, dr_1 \qquad (200)$$

The total error of incidence at S_3 is

$$de_3 = de_2 + de_3' \qquad (201)$$

and after refraction the error of projection E_1 is

$$E_1 = (de_2 + de_3')\, \frac{di}{dr} \qquad (202)$$

Substituting values from (197) and (200)

$$E_1 = -\left(\frac{n\cos r}{\cos i} - 1\right)\frac{di}{dr}\, dr_1 \qquad (203)$$

The two displacement errors have canceled out of this expression leaving only the original de_1.

We have the relation

$$\frac{V_1}{dr_1} = \frac{di}{dr}$$

and

$$\frac{di}{dr}\, dr_1 = V_1 \qquad (204)$$

hence equation (203) becomes

$$E_1 = -\left(\frac{n\cos r}{\cos i} - 1\right) V_1 \qquad (205)$$

The negative sign indicates that a positive rotation of the surface at S_1 causes a negative deflection of the projected ray.

This error E_1 is measured from the line of correct projection which is parallel to the axis in the paraboloid, convergent to the axis in the ellipsoid, and divergent from the axis in the hyperboloid. If we were interested in minute errors of projection, say those measured in seconds of arc, this generalization would not be permissible, but for the present purpose the equation fulfills all requirements for accuracy.

CASE II: The surface at S_2 is in error by an angle V_2 in the meridian plane

The ray is correct in direction up to S_2, where an error

$$de_2' = 2\, V_2 \qquad (206)$$

is introduced.

The displacement dl_3 is found by substituting $2V_2$ for dr_1 in (195) and therefore the error in direction at the point of incidence upon S_3 is

$$\begin{aligned} de_2'' &= 2\, V_2 + \frac{T_0 \cos^3 i}{\cos^3 r}(2\, V_2) \\ &= 2\, V_2\left[1 + \frac{T_0\cos^3 i}{\cos^3 r}\right] \end{aligned} \qquad (207)$$

Upon emerging from the glass the deviation is increased by the factor $\frac{di}{dr}$ and the error of projection is

$$E_2 = 2\,V_2\left[1+\frac{T_0\cos^3 i}{\cos^3 r}\right]\frac{di}{dr}$$

$$= \frac{2\,n\cos r}{\cos i}\left[1+\frac{T_0\cos^3 i}{\cos^3 r}\right]V_2 \qquad (208)$$

In case the surface under investigation is not a paraboloid this equation, containing T_o, may be applied by considering the surface at S_2 to be parabolic in section with the axis of the parabola parallel to the correctly projected ray. In this case T_o is derived from the actual thickness T_a of the glass at the point S_2 and the angle of refraction r as indicated in equation (187).

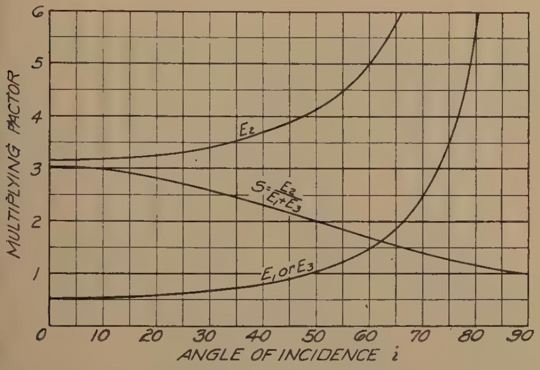

Fig. 153. The directional influence of errors in the second surface of a glass mirror is in general from one to three times as great as the influence of an equal error in the first surface, as is illustrated by the curve marked *S*. Nearly all mirrors in use have maximum angles of incidence from 30 to 60 deg. and the importance of the second surface in correctly reflecting the light is therefore over twice that of the first surface

CASE III: *The surface at S_3 is in error by angle V_3 in the meridian plane*

In this case the ray pursues the correct path up to the surface S_3 and the deflection is

$$E_3 = V_3 - V_3\frac{di}{dr}$$

$$= -\left(\frac{n\cos r}{\cos i} - 1\right)V_3 \qquad (209)$$

which is the same expression as in Case I. In the development of equation (205) a small term involving T_o^2 was dropped and with this exception an error at S_1 produces a deviation of the light exactly equal in size and of the same direction as a similar surface error at S_3. This expression is independent of the curvature of the mirror or the thickness of the glass.

Summation of Errors and the Most Probable Error

We are dealing with surface errors that may be measured in minutes of arc, and when this is the case it is permissible to add and subtract errors imposed on a ray at the three points S_1, S_2, and S_3.

If the errors in the first surface are uniform in direction and magnitude, say a gradual increase of thickness of glass from the center outward and in excess of the required amount, the projection error will be, from equations (205) and (209)

$$E = E_1 + E_3$$

$$= -2\left(\frac{n\cos r}{\cos i} - 1\right)V \qquad (210)$$

If the errors are in the second surface the projection error is given by equation (201).

In case the thickness of the glass is found to vary from the correct values, but it is not known which surface is most in error, we may consider them both to vary an equal amount, giving an error of projection

$$E_p = 1/2\,E_1 - 1/2\,E_2 + 1/2\,E_3$$

$$= \left[1 - \frac{2\,n\cos r}{\cos i} - \frac{n\cos i}{\cos r}T_o\right]V \qquad (211)$$

where V is the combined divergence of the two faces, and the error E_p is the most probable error when the variations of the glass from correct form cannot be definitely attributed to either surface.

Relative Importance of the Two Surfaces

A study of the relative importance of the errors in the front surface as compared with the back surface shows the latter to be the much more important of the two. Thus, if due to manufacturing processes, one face will probably have a higher accuracy than the other, the preference should go to the silvered side of the glass. The following data, taken from the curves of Fig. 153, illustrate the point. The value of S, the sensitiveness of the silvered surface as compared with the unsilvered surface is

$$S = \frac{E_2}{E_1 + E_3} \qquad (212)$$

where the errors of the surfaces are

$$V_1 = V_2 = V_3 \qquad (213)$$

At points near the axis the back surface produces three times the projection error as does a front surface equally deformed. At points removed from the axis the relative importance of accuracy tends to become equal for the two, and at the limit they do reach an absolute equality. But the everyday mirrors in which we are most interested have generating angles from 60 deg. to 120 deg. or angles of incidence from 30 deg. to 60 deg. Within this range the lowest value of S varies from 2.6 to 1.7, and has a common maximum of 3. We can therefore say that accuracy of grinding is optically between two and three times as important for the back as for the front surface.

There is one particular form of mirror that is occasionally used in which the first surface outweighs the second surface in importance. This is when the mirror has a short focal length and an extreme angular depth so that the vertex is omitted and the mirror is almost conical in form. Ordinarily it is made as a first-surface mirror but there is no particular reason why it should not be made of glass. The generating angle a has a minimum value of 155 deg. and a maximum value of 162 deg. so that the lamp sets well back of the smaller end of the mirror. The percentage of first-surface light reflected from the near edge of the mirror amounts to 36 per cent of the total, and from the far edge the percentage increases to 44. Here the importance of the first surface rises to that of the second surface, and the latter is evidently decreasing in importance.

If the mirror is carried to an angle approaching 180 deg. the amount of light reflected from the second surface approaches zero and the mirror reduces itself to a first-surface reflector. The value of S given in equation (212) for the relative sensitiveness of the two surfaces is therefore not a measure of the photometric importance of the two, and to find the photometric value, K, we have but to multiply each error in equation (212) by the amount of light involved, thus

$$K=\frac{E_2\,R_2}{E_1\,R_1+E_3\,R_3} \qquad (214)$$

where R_1, R_2, and R_3 are the amounts of light involved respectively in the projection errors E_1, E_2, and E_3. This way of weighting the two surfaces perhaps exaggerates the importance of the second surface while the equation for the relative sensitiveness S does not give it enough importance, for there is often the possibility of adjusting the light source so as to minimize the errors of projection of the combined beam considered as a unit.

In case the light source is shifted along the axis and the best position found by trial, the main beam will be the controlling factor and it will be brought into the best parallelism regardless of the beam from the front surface or from the multiple internal reflections. The optical errors of both surfaces will therefore be shifted to the front surface beam. It sometimes happens that certain zones of the back surface are correct and others are in error, and while a compromise position of the light source is possible there is no complete rectification of the main beam possible and the front surface beam may therefore be left in better condition. There are thus certain conditions under which the entire effect of surface errors may be thrown into the front surface beam leaving the main beam in normal shape.

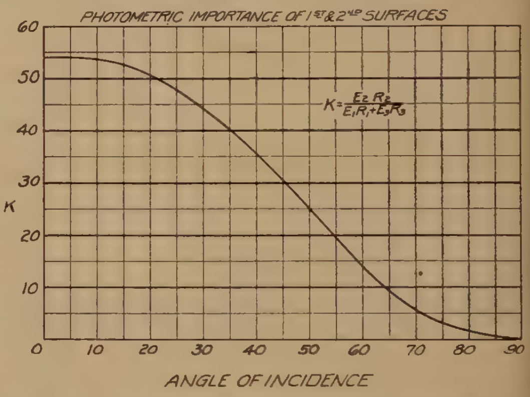

Fig. 154. This curve illustrates the relative importance of accuracy in the first and second surfaces when an allowance is made for both the directional effect of a given surface error and the quantity of light involved. At normal incidence this method of weighing the surfaces shows the second surface to be 54 times as important as the first, but this ratio is modified as explained in the text

These conditions are:

(1) Front surface alone in nearly uniform error in all zones and source at compromise focal point of rear surface.

(2) Rear surface alone in nearly uniform error in all zones and source at compromise focal point of rear surface.

(3) Both surfaces in nearly uniform error in all zones and source at compromise focal point of rear surface.

The condition which does not permit an effective escape by adjusting the light source is

(1) Either surface in error in zones, which is the type of error illustrated by curve A, Fig. 148.

Stray Light

There are two particular cases where lack of co-ordination between the two faces of a glass mirror has an extremely detrimental effect. In military searchlight practice the observer must often stand near the searchlight. This position makes it necessary for him to look through a considerable space of air illuminated by the stray light. The effective range of a searchlight under such conditions is largely determined by the back glare of the beam, and the nearby fringe of stray light is vastly more potent in producing this glare than is the useful light in the center of the beam. A few million candles in the edge of a 60-in. beam may nullify the power of a hundred millions in the center, and therefore one of the greatest possible economies is gained by taking care of the light from the front surface which can do but little good but may do vast harm.

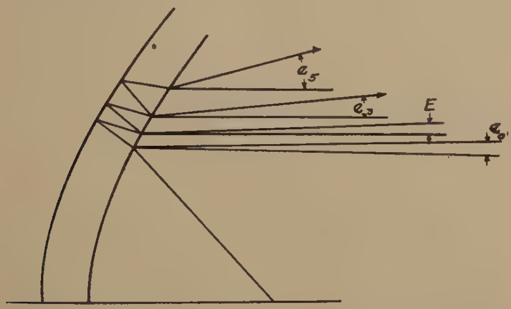

Fig. 155. **The beam that is made up of repeated internal reflections is not reflected as a unit, but is scattered as illustrated above when either surface is in continuous error, such as by a gradual increase of thickness above the proper amount**

The second case is found in automobile headlight practice. There are various degrees of glare, all bad, but one of the worst types is that arising from incorrectly made glass mirrors, or other parts of the optical system that give a narrow intense beam for driving and a wide low-intensity beam for general nuisance purposes. The scattering power of only a small optical error, carried from center to edge of a glass mirror is sometimes surprising. It was pointed out in a previous section* that a certain amount of the beam light undergoes a number of reflections within the glass before escaping. Let us assume that the front surface alone is in error by a constant angle V over a zone at least wide enough to permit a number of internal reflections. The light directly reflected from the first surface will be in error

$$e_0 = +2\,V \qquad (215)$$

with the axis.

The main beam will be in error

$$E = -2\left(\frac{n \cos r}{\cos i} - 1\right) V \qquad (216)$$

and the first ray of the internally reflected beam (see Fig. 155) will be in error

$$\begin{aligned} e_3 &= E - 2\,V\frac{di}{dr} \\ &= \left(2 - \frac{4\,n \cos r}{\cos i}\right) V \qquad (217) \end{aligned}$$

and the second ray of the internally reflected beam will be in error,

$$\begin{aligned} e_5 &= E - 4\,V\frac{di}{dr} \\ &= \left(2 - \frac{6\,n \cos r}{\cos i}\right) V \qquad (218) \end{aligned}$$

where the subscript 5 indicates the number of internal reflections.

In general we have for p internal reflections

$$e_p = \left[2 - (p+1)\frac{n \cos r}{\cos i}\right] V \qquad (219)$$

The projection error grows as the number of reflections increase and if it were not for the rate at which the successive beams decrease in intensity a small error would produce a wide flare of stray light. Some figures are given in Table XIX for the increase in error at different mirror zones and for the first four rays of the internally reflected beam.

For the sake of brevity, the beams suffering 0, 1, 3, etc. internal reflections will be called the beams of the zero, first, third, etc. order, and it may be well to consider how these individual beams act and are influenced by adjustments of the light source. The zero order, or first-surface beam is out of parallelism by four times the surface error, that is an error of V_1 in the surface produces a deviation of $2V$ to the right and $2V$ to the left, a total of $4V$. The form of the beam follows the same general rules as for a displaced light source. If $4V$ exceeds by twice the width of the zero order beam when in true focus then the beam will be hollow, providing of course that all zones have the same error V. It might thus happen that the zero order beam would be a ring of light surrounding the main beam, which ordinarily is a condition to be avoided. The beams of the third, fifth, seventh . . . order would also be annular and perhaps overlapping, with the ring of highest order on the outside.

In case the first surface is in practically constant error from center to rim, the main beam can be brought into better focus by a photometric exploration, moving the arc along the axis as the central intensity is read, and the three beams will then take up a new relationship. It might be here remarked that an exploration should often be made with each individual mirror for experience has shown them to vary enough to cause appreciable loss of beam intensity with the high-intensity arc, but when used with plane carbons the exploration is not so necessary.

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*Part XII, General Electric Review, Sept., 1924, p. 625.

With the arc adjusted to give the maximum beam intensity, the errors in the three beams are:

(1) First-surface beam in error

$$e_0 = 2V + E_1 + E_2 = \left(\frac{2n\cos r}{\cos i}\right)V \qquad (220)$$

which represents an increase of error due to the second-surface beam being brought into focus regardless of the first-surface beam.

(2) The main beam, if complete adjustment is possible, has an error

$$e_1' = 0 \qquad (221)$$

(3) The multiple-reflected beams have errors

$$e_3' = e_3 - (E_1 + E_3) = -\frac{2n\cos r}{\cos i}V \qquad (222)$$

$$e_5' = e_5 - (E_1 + E_3) = -\frac{4n\cos r}{\cos i}V \qquad (223)$$

and in general

$$e_p' = e_p - (E_1 + E_3) = -\frac{(p-1)n\cos r}{\cos i}V \qquad (224)$$

In Table XX these various errors are listed for points 0 deg., 60 deg., and 120 deg. on the mirror. These figures are in some ways closer to good practice than the previous data, because the main beam is now in its most favorable condition.

Correcting the errors of the main beam by adjusting the source is in general not possible for the entire surface of the mirror. It was shown in the discussion of the beam characteristics with the source out of focus that each mirror zone was sensitive in a different degree, and it would be only in the extremely unlikely event of the mirror zones being in error in exact proportion to its sensitivity to focal error that all zones could be corrected by a single adjustment of the source. We must therefore consider each mirror zone independently for a beam adjustment for one may be incomplete or a misadjustment for another. The one fact that Table XX does bring out strongly is that all beams are corrected by the same angular amount when any one is changed, and that the beams of

TABLE XIX

FIRST-SURFACE ERRORS AND PROJECTION ERRORS

Multiplying Factors Due to Repeated Internal Reflections—Main Beam Not Adjusted

ZONE ON MIRROR	NUMBER OF INTERNAL REFLECTIONS					
	0*	1**	3	5	7	9
Angle	Factor					
0	+2	−1.0	−4.0	− 7.0	−10.0	−13.0
60	+2	−1.4	−4.8	− 8.2	−11.6	−15.0
120	+2	−3.0	−8.0	−13.0	−18.0	−23.0

*First surface beam.
**Main beam.

TABLE XX

FIRST-SURFACE ERRORS AND PROJECTION ERRORS

Multiplying Factors Due to Repeated Internal Reflections—Main Beam Adjusted

ZONE ON MIRROR	NUMBER OF INTERNAL REFLECTIONS					
	0*	1**	3	5	7	9
Angle	Factor					
0	+3.0	0	−3.0	− 6.0	− 9.0	−12.0
60	+3.4	0	−3.4	− 6.8	−10.2	−13.6
120	+5.0	0	−5.0	−10.0	−15.0	−20.0

*First surface beam.
**Main beam.

higher order do not multiply any change made in the direction of the incident ray.

In the case of the automobile headlight we are certainly interested in light three times internally reflected. This beam has an intensity corresponding to that given off by a light source three per cent as bright as the filament. The beam intensity will be less than three per cent because this light is scattered, but if we assume it to be only one per cent of the central beam intensity of the true beam we can get some idea of its importance as a cause of glare. A central beam intensity of 15,000 candles is a not unusual figure, and the glare intensity will therefore be of the order of 150 candles, which is enough light to be blinding under many conditions.

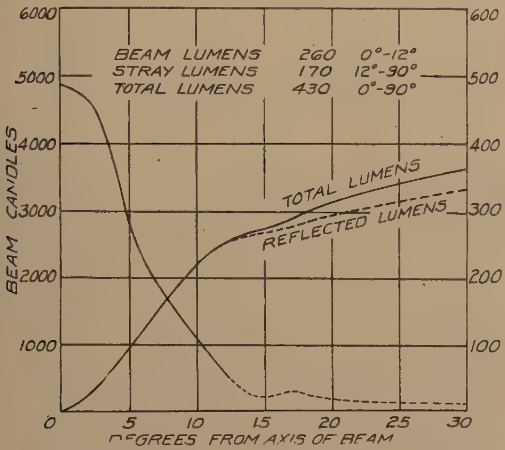

Fig. 156. The solid curve on the left is a typical beam characteristic from an imperfect mirror and the dotted extension is stray light due to errors in the reflector and direct radiation from the lamp. The dotted lumen curve, obtained from the solid lumen curve by subtracting the direct radiation, shows about 90 stray lumens in the 12- to 30-deg. zone alone

The small deep mirror of the headlight often has surface errors of several degrees, but for the sake of illustration, let us assume V to equal one degree. From Table XIX the thrice-reflected light from the 120 deg. zone has a radial spread of 8 deg., which is measured from the edge of the true beam.

The glare zone surrounding the true beam will therefore be 2 deg. wide for the zero order beam and 8 deg. wide for the third-order beam. If by the adjustment indicated in Table XX we can reduce the glare zone to 5 deg. and 5 deg., then there will be a decrease of glare for the three outer degrees and an increase over the three inner degrees next to the true beam. This adjustment will be an improvement from the standpoint of glare unless it happens that the inner zone is the critical one. As a problem in applied optics, it seems evident that glare arising from the individual action of the front and rear surfaces of a glass mirror can be lessened but not cured by adjustment of the light source, and a total elimination of this type of trouble is possible only through proper design and construction of both the surfaces.

The scattering of light by minor surface errors often has a serious effect in the photometric rating of a projector. It is often difficult to convince a person that almost invisible defects in the curvature of the glass are responsible for losses of 10 to 30 per cent of the beam light. This loss is particularly likely to take place in some of the compound reflectors where part of the light is reflected from two surfaces before leaving the unit. Light so "lost" can usually be located in the zones surrounding the beam, but it occasionally happens that the user of the headlight or projector would much prefer that it be really lost rather than be reflected at a very undesirable angle. In Fig. 156, the upper curve gives the summation of lumens to 40 deg. from the axis, while the lower (dotted) lumen curve gives the total lumens with the direct light from the lamp eliminated. The curve of beam intensities shows a distinct zone due to stray light outside of the true beam, and in addition a considerable quantity of more widely scattered light.

(To be continued)

The Totalizing and Remote Indication of Electric Power and Its Reactive Component

By H. K. Nock and H. S. Edgerly
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General Electric Company

The indicating and recording of the power output and reactive volt-amperes of a single generator have presented no great difficulties, but the totalizing of these measurements for several machines has been attended with complications. For example, in totalizing the reactive component mathematical computations have been necessary. The instrument described in this article has been devised to accomplish these functions more easily. It has been designed to indicate either the power or reactive component, depending upon its connections, and can be arranged to record graphically in either case the output of several generators. The desirability for the remote indication of such readings has long been acknowledged. By means of the simple auxiliaries explained in this article, the indications of the totalizing instrument may be transmitted to a practically unlimited distance.—Editor.

With the increase in the size of power systems there arises a demand for an instrument that can totalize the entire load of several generators and furnish a complete record on one chart of the information required by those who deal with the whole power plant as a unit. The task of adding several meter readings for bookkeeping or other purposes is thus eliminated. Not only should a permanent chart record be obtained, but it is often desirable to transmit the readings of the totalizing instrument to various parts of the station for the benefit of the switchboard operator, boiler room attendant, chief engineer, or others who may be interested. Totalizing has been accomplished in the past by connecting the secondaries of current transformers in multiple or by a multiple-circuit instrument requiring a large external box. Either method is frequently objectionable and in many cases quite inapplicable. The multiple connection of the secondaries of current transformers is limited by the fact that the transformers must be of the same ratio; otherwise, the addition of auxiliary transformers is necessary to obtain a combination of ratios that are equal. In either case the circuits are inter-connected and an ideal layout demands independent circuits to simplify the wiring.

The congestion on the rear of the average modern switchboard also has a tendency to complicate the arrangements. The use of external devices with the instruments should therefore be avoided. After an extensive study of the problem, an instrument has been developed which has all the qualifications necessary to accomplish any anticipated requirement of totalizing.

In order to present a general idea of some of the novel features embodied in the construction of this instrument, a description of it will be given.

Fig. 1 shows the general appearance of the instrument, which operates on the induction principle. The moving member consists of a shaft approximately two feet long on which are mounted four disks. Grouped around these disks are 16 standard watthour-meter elements, so arranged that they cause to exist a torque-producing current in the disk. Each element is capable of adjustment with respect to the disk so that its torque on the movable member may be varied from zero to the maximum. This permits of accurate adjustment between the various elements. Final adjustment is made by two control springs. The accuracy of the instrument over its entire scale is thereby assured.

The chart is so arranged that approximately 12 inches is visible, which amounts to a four-hour record when the paper is fed at a rate of three inches per hour. Longer records can be read by unrolling the paper, as arrangements are made to re-roll it by hand in such cases. The record on the chart is made by a pen connected through a simple link mechanism to the moving member, which is given a rotating motion. Although the moving member has a rotational movement the link mechanism is so designed that the pen draws a straight-line record over a chart five inches wide. All the moving parts of the pen mechanism have instrument jewels and pivots, thereby reducing friction to a minimum.

A Warren motor acting through a series of three gears drives the chart. The re-roll mechanism is direct-connected to the chart drive by means of a spring belt. The belt tension is carefully adjusted so that the re-roll speed will eliminate any slackness of the paper. Aside from its simplicity, the Warren motor has the additional advantage that it can be synchronized with other Warren motor-actuated charts throughout the entire station. If it is preferred, a spring clock mechanism can be substituted for the Warren motor.

The inking system is extremely simple and seldom needs to be cleaned. An elongated trough holds about a month's supply of ink. This ink is siphoned over a travel of two inches to the paper. The trough is located directly behind the chart, so that both the trough and the pen are accessible to the operator.

The damping is obtained by direct connection to a paddle moving in a sealed chamber of mercury. This arrangement has several advantages; the connection is so direct that damping takes place as soon as the element starts to move, and since the damping fluid is mercury the action is positive and does not change with time or climatic conditions. The result is a smooth-line chart record, as shown in Fig. 2, representing the average of many small fluctuations of power of short duration.

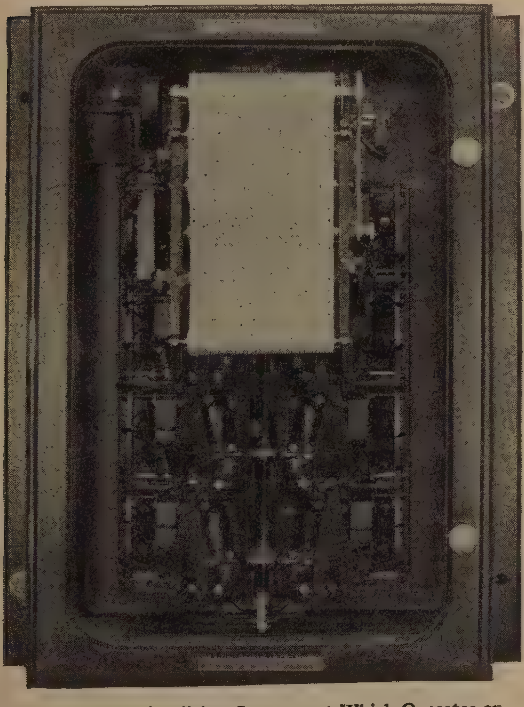

Fig. 1. New Totalizing Instrument Which Operates on the Induction Principle, Showing Chart on Which Readings Are Recorded

The instrument is entirely self-contained and capable of reading either watts or reactive volt-amperes under ordinary conditions. For installations requiring remote indication on instruments 15 in. or larger in diameter, or where the transmission distance exceeds 2000 ft., indication transmitters are necessary. These will be described later. The standard instrument can be used to totalize any number of circuits up to eight; three-phase, three- or four-wire; two-phase, four-wire; or any combination of these circuits. They can be calibrated for a given number of circuits with the full scale deflection and later changed to a larger number of circuits (not exceeding eight) by a change in the external connections or a possible change of the elements, either of which can be accomplished without removing from the switchboard.

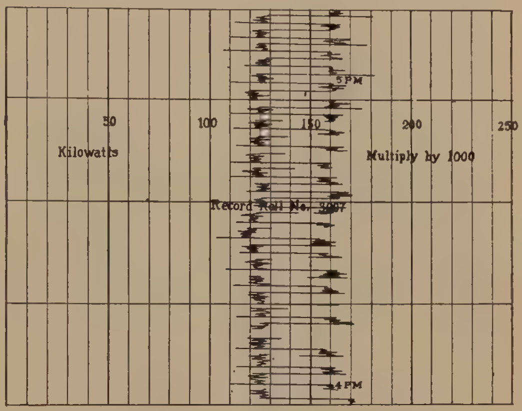

Fig. 2. Sample Smooth-line Chart Record Drawn by Totalizer

The instrument has a very high torque which permits, for transmitting purposes, the use of selsyn generators and motors. This system easily surpasses any other now employed. The generator mounted in the totalizing instrument is connected by five wires to small selsyn motors in locations remote from the operating room. These motors are mounted in instrument cases and are adjusted to indicate on suitable dials the actual station load as indicated by the totalizer.

The base casting of the totalizer is designed to form a panel section having standard dimensions: 31 in. high, 24 in. wide, ¼ in. bevel, and the bolt holes in the standard location. The case projects from the front of the panel about 10½ in. The total weight of the instrument is approximately 200 lb. By the use of an additional disk and by increasing the number of elements it is possible to totalize up to 12 circuits, retaining the foregoing dimensions.

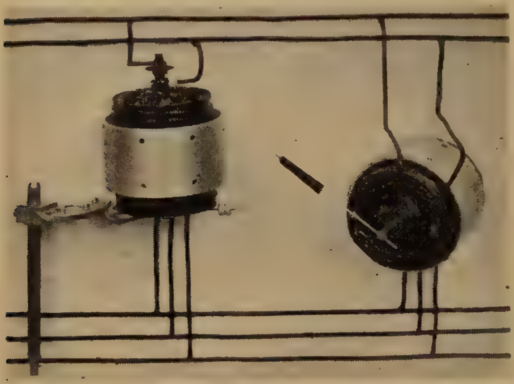

Fig. 3. Schematic Connection of the Selsyn System, with Generator and One Motor Shown. Gear sector of totalizer is seen at the left

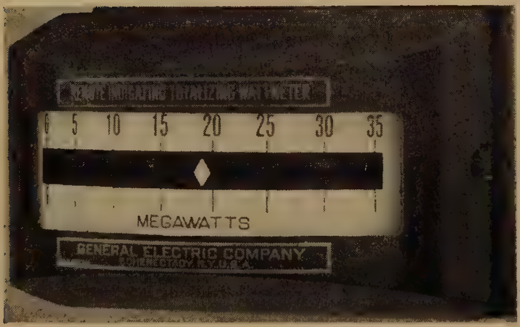

Fig. 4. Selsyn Motor as Mounted in Horizontal Edgewise Case for Remote Indication

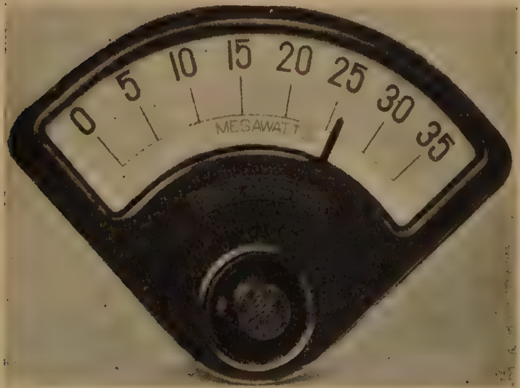

Fig. 5. Remote Indicator Designed for Panel Mounting

All the instruments have a door so arranged that it can be removed by being lifted from the hinges, which makes calibration very convenient. The door knobs are designed with a spring latch, requiring only a quarter turn to open or close.

Remote Indication

When the totalizers are used to transmit indications for remote reading, they are supplied with a selsyn generator. When remote indication is not required they are so constructed that the selsyn generator can easily be installed whenever it is desired. On the selsyn generator is a gear sector which meshes with the gear sector on the shaft of the totalizer, and changes the position of the selsyn armature in proportion to the movement of the totalizer shaft. Since the selsyn motors in the remote indicators are connected to the generator in the totalizer, the position of the motor arms is correspondingly changed. Due to the special design of the selsyn motors, it is possible to operate as many as 20 remote indicators from this totalizer. A schematic connection of the selsyn system is shown in Fig. 3.

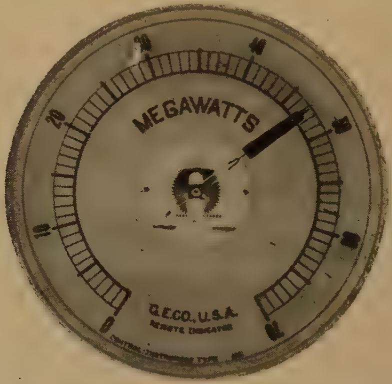

Fig. 6. Round-pattern Remote Indicator for Panels Where This Style of Instrument is Preferred

Several types of remote indicators have been designed to meet the requirements of the different locations. The indicator shown in Fig. 4 is merely a selsyn motor mounted in a horizontal edgewise case and is suitable for locating in the chief engineer's office. The indicator seen in Fig. 5 is adapted to mounting on panels in various parts of the generating station. The indicator illustrated in Fig. 6 is suitable for mounting on panels where round-pattern instruments are preferred.

The use of round-pattern indicators 15, 24, or 36 in. in diameter in boiler rooms requires the introduction of an indication transmitter into the circuit. This transmitter consists of a contact-making selsyn motor controlled by the selsyn generator in the totalizer, which starts, stops, or reverses a small motor. This small motor in turn causes an armature movement of a larger frame selsyn motor proportional to the original movement of the totalizing-wattmeter shaft. Being possessed of greater power than the smaller selsyn motor, this transmitter readily operates and controls as many as four large remote indicators even though the burden is very heavy. The general arrangement of connections for this transmitter is shown in Fig. 7.

When using the large round-pattern remote indicators, especially in boiler rooms, it is often advantageous to locate them in the center of the aisle, in which case double-face instruments are employed, Fig. 8. Very often an operator wishes to signal the anticipated load to the boiler room attendant. To accomplish this a second needle painted red is placed in the remote indicator, mounted concentric with the indicating needle. The red needle is actuated by a manually operated selsyn, Fig. 9, located on the benchboard. Where it is desirable that the time of the anticipated load be given, a smaller remote indicator having one needle is operated by a manual transmitter. The scale on this remote indicator and the transmitter is marked like a clock dial. As it is not necessary to read closer than 15 minutes one needle is considered sufficient.

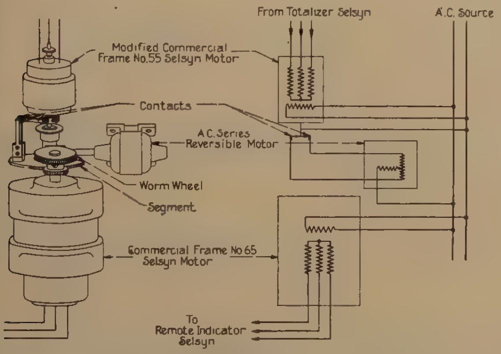
From Totalizer Selsyn
A.C. Source
Modified Commercial Frame No.55 Selsyn Motor
Contacts
A.C. Series Reversible Motor
Worm Wheel
Segment
Commercial Frame No.65 Selsyn Motor
To Remote Indicator Selsyn

Fig. 7. General Arrangement of Connections for Operation of Large Remote Indicators

In some installations it is desirable to transmit the indications up to a distance of 30 miles. For this service an indication transmitter is used having general connections as shown in Fig. 10. In this transmitter the selsyn motor moves a contact arm over a resistance, thus varying the direct-current voltage on a pair of telephone wires which controls the remote indicator that in this instance is a single millivoltmeter.

The same general application for remote indication from single generators can be used on the standard curve-drawing instruments, although the number of remote indicators that can be operated is limited.

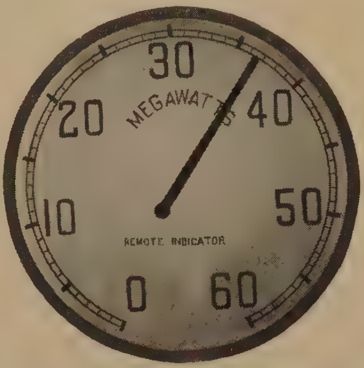

Fig. 8. Double-face Instrument Specially Designed for Remote Indication in Boiler Rooms

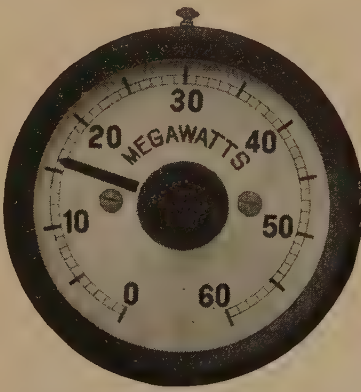

Fig. 9. Manually-operated Selsyn Generator for Control of Anticipated-load Needle Mounted in Boiler-room Indicator

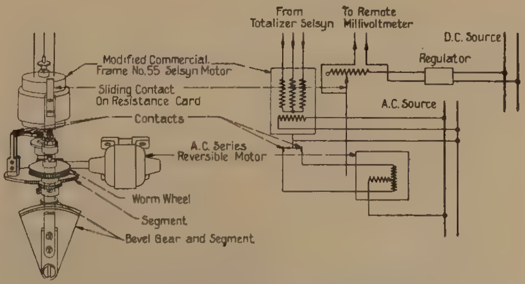

Fig. 10. General Connection of Apparatus for Transmission of Indications Up to Thirty Miles

Studies of Electric Discharges in Gases at Low Pressures

PART IV

DATA ON DISCHARGES IN MERCURY VAPOR OBTAINED WITH CYLINDRICAL COLLECTORS

By Dr. Irving Langmuir and Harold Mott-Smith, Jr.
Research Laboratory, General Electric Company

The preceding installments in this series have dealt largely with the development of methods for finding out what is really going on in gaseous discharges particularly in mercury arcs. The present installment gives a summary of the results of many experimental determinations and analyzes them. Some new viewpoints, particularly that of the random and drift currents, promise to clear up some of the most baffling puzzles that have held back progress in this field.—Editor.

In the previous installment[11] it was shown that the volt-ampere characteristics of cylindrical collectors can be used to determine the random current densities (I_e and I_p) and concentrations (n_e and n_p) of electrons and ions in the discharge and also the temperature (T_e) of the electrons. A collector of such large radius that the current is limited by space charge yields data for I_e, I_p, and T_e, while a collector of very small radius where the current is limited by the orbital motions of the collected particles gives n_e, n_p, and T_e. Since the positive ion concentration (n_p) is expressible in terms of $I_p/\sqrt{T_p}$ it should be possible by the simultaneous use of two collectors (one of large and the other of small radius) to determine the value of T_p, the temperature or equivalent average velocity of the positive ions.

The data in the preceding section showed such discrepancies between the values of n_e obtained from the two collectors that they did not justify a calculation of the temperature of the positive ions, although the data will prove useful in other respects.

In the present section we shall review some of the data obtained with the tube shown in Fig. 3, page 767, using the cylindrical collectors F and G. These data will be compared with those previously obtained[12] with the plane collector H and we shall see that they permit a rough estimate to be made of the temperature of the positive ions.

Dimensions of Tube of Fig. 3

The tubing which contained the various collectors had a diameter of 3.2 cm. The distance along the axis of the tubing from the junction of the side arm to the lower end of the anode A was 23 cm. and to the tip of anode B, 25 cm. The collector F was 7.6 cm. from the junction and the distance from F to G was 16.5 cm., and the tip of the anode B was 1.3 cm. from G. Collector E was 5 cm. from the junction and the distances E to D and D to C were each 7.6 cm. while the top of the anode A was 3.5 cm. above C. The collector H was a square nickel plate 1.90 cm. on a side; J and K were each squares of sheet nickel 0.95 cm. on a side. The collectors C, D, E, F, and G were small hairpin filaments[13] with leads carefully enclosed in fine glass tubes so as to prevent any current being collected except by the filament itself.

The diameters and exposed lengths of the filaments were:

Collector	Length cm.	Diameter cm.	Area cm.^{2}
C	1.11	0.00778	0.0271
D	1.27	0.0180	0.0720
E	1.59	0.00778	0.0389
F	1.27	0.00778	0.0310
G	1.59	0.00778	0.0389

Explanations of the Tables

A summary of the data obtained from a study of the volt-ampere characteristics of the filamentary collectors F, G, D, and E is given in Tables XII to XV. The methods used in calculating the fundamental quantities T_e, I_e, I_p, n_e, and n_p have been described in the previous installments and will therefore be only briefly outlined here.

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[11] Part III (Sept., 1924, p. 616).

[12] Part II (Aug., 1924, p. 538).

[13] These collectors were considered in effect to be cylindrical, care having been taken that the two legs of the loop were so far apart that they should have relatively little influence on one another. However, such a construction is in general undesirable. It was used in the experiment under discussion for two reasons: (1) By heating the filament when it was at a high negative potential, electrons in any number and of known velocity could be injected into the arc; (2) by adjusting the potential of the collector and varying its temperature, a point could be found where the electrons emitted were just unable to escape; this furnished an independent means of measuring the potential of the space around the collector.

Table XII gives the data[14] obtained in Run 24 in which the bulb was at 48 deg. C. and the mercury vapor pressure[15] was therefore 14.6 bars. A constant exciting arc of 6 amp. was maintained to the anode A and various currents I_B (Column 1) were passed to anode A through the horizontal arm. Column 2 gives E_{BC}, the potential of B with respect to the mercury cathode (below the condenser). For each value of the current I_B three different voltages of approximately -40, -65, and -90 were applied to the collector F, these potentials E_{FB} being measured from that of the anode B, and for each potential the current i_F in milliamp., which flowed from F into the mercury vapor, was measured. Column 3 in Table XII gives the values of i_F obtained with the intermediate voltage $E_{FB}=-65$, the values of i_F for the other voltages being omitted for the sake of brevity. As will be shown in the following, each value of i_F may be used to calculate the positive ion current density I_p. The values of I_p given in Column 6 are the averages of the values obtained at the three different voltages. The three values, however, differed from the corresponding average by a mean error of only 3.2 per cent and in an irregular manner, so that the data in Columns 3, 4, and 5 of Table XIV based as they are on the measurements at the intermediate voltage may be regarded as typical.

From the positive ion currents i_F the values of β^2 were calculated[16] from the space charge equation (13), taking ν as given by equation (11) with $T_p=10{,}000$. The potential V used in these calculations is the potential of the collector with respect to the surrounding space. Since subsequent measurements showed that the space potential near F was about 9 volts below that of the anode B, the value of V used in the calculations was -56. From β^2 the value of a/r, the relative sheath radius, can be obtained by equations (14) and (15) or, more conveniently, from plots of the function β^2 prepared from tables[17]. These results are given in Column 4. The justification for assuming velocities for the positive ions corresponding to $T_p=10{,}000$ will appear later; it should be remembered that even doubling T_p has only a very small effect upon the value of $\frac{a}{r}$.

To calculate the positive ion current density I_p we make use of the general equation (24) which becomes

$$i_F=A_F I_p f \qquad (72)$$

TABLE XII

Positive Ion Data for Collectors F and H in the Tube of Fig. 3. Bulb at 48 deg. C. Mercury vapor pressure 14.6 bars. T_p = 10,000 deg. K. Run 24

1	2	3	4	5	6	7	8	9	10	11
					COLLECTOR F			COLLECTOR H		
i_B Amp.	E_{BC} Volts	i_F ma.	$\frac{a}{r}$	f	I_p from f	I_p cal.	i_H ma.	I_p exp.	I_p cal.	$\frac{d\nu}{dx}$ Volts cm.$^{-1}$
0.1	40.0	−0.0172	32.8	8.85	0.063	0.062	−0.060	....	....	0.50
0.2	39.8	−0.040	19.3	8.70	0.143	0.154	−0.158	0.038	0.038	0.42
0.3	39.5	−0.064	14.6	8.38	0.247	0.264	−0.265	0.065	0.062	0.40
0.5	39.3	−0.127	9.6	7.38	0.53	0.52	−0.45	0.114	0.114	0.41
0.75	39.0	−0.185	7.68	6.66	0.90	0.88	−0.78	0.203	0.185	0.44
1.00	38.8	−0.26	6.35	5.89	1.41	1.29	−1.02	0.265	0.260	0.46
1.50	38.6	−0.37	5.13	4.93	2.31	2.20	−1.68	0.445	0.42	0.47
2.0	38.5	−0.47	4.71	4.60	3.32	3.22	−2.30	0.61	0.59	0.46
3.0	38.3	−0.66	4.05	4.02	5.42	5.50	−3.55	0.95	0.97	0.44
4.0	37.0	−0.88	3.66	3.65	8.10	8.0	−5.1	1.38	1.37	0.43
5.1	36.7	−1.10	3.25	3.25	10.7	11.1	−6.9	1.86	1.79	0.41
6.0	36.5	−1.29	3.05	3.05	13.9	13.7	−8.2	2.20	2.21	0.40

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[14] The designation "Run" was used for convenience to identify various experimental data and refers to the page number of the "record sheet" on which the original data were recorded. The numbers thus give the sequence of the observations.

[15] By the use of the special construction (illustrated in Fig. 3) resembling that of a condensation pump, the blast of mercury issuing from the cathode spot is deflected down into a condensing chamber. Careful measurements with ionization gauges in other experiments have proved that with this construction the mercury vapor pressure in the upper part of the tube is independent of the main arc current and is in fact the pressure of saturated mercury vapor at the temperature of the water bath surrounding the condenser.

[16] In referring to equations, it may be noted that equations 1 to 48 appeared in Part I (July, 1924, p. 449); equations 49 to 55 in Part II (Aug., 1924, p. 538); and equations 56 to 71 in Part III (Sept., 1924, p. 616).

[17] Langmuir and Blodgett, *Physical Review*, *22*, 347 (1923).

A_F being the collecting area (0.0310 cm.^{2}) and f being the function defined by equation (25). This involves a knowledge of η defined by equation (26) which is

$$\eta = \frac{11{,}600\,V}{T_P}. \qquad (73)$$

Taking, as a provisional assumption, $T_p = 10{,}000$ deg. K, we have $\eta = 1.16\ V$, and thus find $\eta = 65$. From this value[18] and the corresponding value of a/r, f was read off from a series of plots of this function[19] which had been prepared and the results are recorded in Column 5.

The values of the positive ion current density I_p in milliamperes per cm.^{2} in Column 6 are the averages calculated by equation (72) from the corresponding values of i_F and f. When these values of I_p are plotted on double logarithmic paper with i_B as abscissa, a very good straight line is obtained which corresponds to

$$I_p = 1.29\, i_B^{1.32}$$

where i_B is in amperes and I_p in amperes per cm^2. The values of I_p read off from this straight line are tabulated in Column 7; it is seen that they agree excellently with those in Column 6 which were calculated from the experimental data.

Column 8 gives the positive ion currents which flowed to the plate-shaped collector H as measured with a potential $E_{HB} = -40$ volts applied to this collector immediately after the corresponding measurements on collector F. From these readings the positive ion current density I_p (in Column 9) was calculated by dividing the current i_H by the collector area (3.61 cm.^{2}), correcting for the edge effect in the manner that has been described.[20] In this case also it was found that the values of I_p plotted on double logarithmic paper with i_B as abscissa gave a straight line corresponding to

$$I_p = 0.260\, i_B^{1.20}$$

Column 10, which gives the values of I_p calculated from this equation, shows by comparison with Column 9 that the relation is accurately fulfilled.

The fact that the values of I_p obtained by H are much lower than those by F, being only 24 to 16 per cent of the latter, is in accord with the fact that the arc tends to concentrate along the axis of the tube, particularly at higher pressures. The intensity of the light emitted from the central part is considerably greater than that near the walls. The fact that the double-log plots obtained from the two electrodes are both straight and nearly parallel is, however, held to be of significance as indicating the substantial accuracy of the methods used in calculating I_F from the data from the cylindrical collector F. It should be noted that the sheath radius a was of vital importance in calculating the values of I_p for the larger currents, for the current under these conditions is limited by space charge, as is evidenced by the practical equality of f and a/r. On the other hand, at the low currents, i_B, the current is limited almost entirely by orbital motion, since f is about independent of a/r and is nearly equal to the value $F = 9.05$ calculated from the limiting equation (38). In this lower range of currents, the resulting value of I_p (Column 6) comes out to be proportional to the square root of the assumed value of T_p (since η and f_∞ depend on T_p), while in the upper range the values of I_p are nearly independent of T_p.

It thus appears that the straightness and parallelism of the double-log plots can occur only with a value of T_p fairly close to the value 10,000 deg. assumed in these calculations. This method of determining the temperature or effective velocity of the position ions is only a rough one but probably fixes this quantity within an accuracy of about 30 per cent. Experiments of this kind for other mercury vapor pressures have not yet been carried out with sufficient accuracy to determine how T_p varies with the pressure so it has been assumed that the value $T_p = 10{,}000$ may be provisionally used in all calculations of T_p at low intensities of ionization where the currents are limited by orbital motion. It must be remembered that at high currents a knowledge of T_p is not needed to get I_p for the currents are then limited by space charge, but under these conditions T_p is needed if we wish to calculate n_p.

The last column of Table XII gives data on the potential gradient in volts per cm. along the axis of the tube between F and G, determined merely by finding for each electrode the potential which brought the current to zero. This method is only justifiable if the conditions at the two electrodes are exactly similar. The results are not considered to be very accurate and experiments are now in progress to measure these gradients by better methods. Another probable source of error in all measurements of potential gradient between electrodes F and G in the tube of Fig. 3 is the disturbance of the arc by the collectors J and K.

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[18] The actual values of η used in the calculations of f were only approximately equal to 65, since the voltages E_{FB} varied by 2 or 3 volts from the average value -65.

[19] Tables of f with curves will probably be published in a later installment.

[20] Part II (Aug., 1924, pp. 540-542).

Table XIII contains a summary of Runs 30 and 31 made with collector G while the condenser was maintained at 16 deg. C. The currents i_G in Column 3 are the positive ion currents obtained with a potential $E_{GB} = -80$ volts. The potentials V, with respect to the space, which were used in calculating a/r and f were obtained from the measurements of the space potential given in Column 10, which were based on the plots of the squares of the electron currents i_G^2 by the method previously described.[21]

Column 6 gives the value of I_p obtained from i_G and f and thus involves at the lower current densities the assumption $T_p = 10{,}000$. Column 7 gives the values of I_p that result if f is assumed to be equal to a/r, i.e., if the current is assumed to be limited by space charge. At the higher currents the figures in Columns 6 and 7 agree but they diverge widely at the lower currents. Column 8 shows what values of I_p would result if the current were limited by orbital motion only ($f = f_\infty$). Here Columns 6 and 8 agree for the lower values but diverge at the higher values.

Plotting all three sets of values of I_p on double-log paper against I_B, we can see that all except the two lower points of Column 6 lie on a straight line of slope 1.35 (exponent), which agrees well with that from Table XII. The unusually low arc drop (Column 2) corresponding to these two points suggests that they are in some way abnormal. A comparison of the plots of Columns 6, 7, and 8 and consideration of the modifications that would result from a change in the assumed value of T_p seem to confirm the general correctness of this value.

Column 9 gives the positive ion density calculated from I_p in Column 6, and T_p by equation (44), while Column 12 shows the electron density from I_e and T_e. The electron temperature $T_e = 24{,}000$ deg. and the electron random current density I_e were obtained from the volt-ampere characteristics by methods previously given.[22]

Table XIV is self-explanatory and the methods of calculation are the same as those already described. In many cases the low-current positive-ion data were calculated directly from f_∞ without a calculation of a/r for the current was limited strictly by orbital motion. In other cases, at high-current densities, it was known that the currents were strictly limited by space charge, so that f did not need to be calculated. In all cases it was found that the electron currents, both at high and at low current, were limited by orbital motion, so that the method involving the plotting of i^2 could be used in determining E_{SB} and I_e. The data for the potential gradient in the last column were determined by taking the differences in the values E_{SB} for electrodes G and F, so that these determinations should be more reliable than those given in the last column of Table XII.

Ratio of Random to Drift Current

The straightness of the semi-log plots of the current-voltage characteristics of both the cylindrical and plate-shaped collectors

TABLE XIII

Data obtained with Collector G. Tube of Fig. 3. Bulb at 16 deg. C. Mercury vapor pressure 1.10 bars.

$T_p = 10{,}000$ deg. C. $T_e = 24{,}000$ deg. K. Runs 30 and 31

1	2	3	4	5	6	7	8	9	10	11	12	13
					I_p ma. cm.$^{-2}$							
i_B Amp.	E_{BC} Volts	i_G (for −80 volts) ma.	$\frac{a}{r}$	f	from f	from $\frac{a}{r}$	from f_∞	$n_p \times 10^{-10}$	E_{SB}	I_e	$n_e \times 10^{-10}$	$\frac{I_e}{I_p}$
0.1	32.5	−0.018	54.0	10.81	0.042	0.009	0.042	1.02	0.0	15	0.39	365
0.2	32.5	−0.029	38.5	10.70	0.070	0.020	0.068	1.71	−0.4	34	0.89	485
0.5	38.0	−0.064	22.9	10.3	0.159	0.073	0.149	3.8	−1.0	100	2.6	630
1.0	39.1	−0.132	14.4	9.51	0.37	0.25	0.32	9.0	−1.3	193	5.0	520
2.0	40.0	−0.272	9.4	8.07	0.88	0.76	0.65	21.5	−1.7	438	11.4	497
4.0	39.0	−0.580	6.28	6.11	2.46	2.38	1.38	60.0	−2.0	800	20.8	325
6.1	38.1	−0.875	5.10	5.07	4.63	4.57	2.16	113.0	−1.4	1360	35.0	294
8.1	36.9	−1.15	4.49	4.48	6.65	6.64	2.80	162.0	−1.0	1800	47.0	271

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[21] Part III (Sept., 1924, p. 616).

[22] Part III (Sept., 1924, p. 616).

proves that with a tube like that shown in Fig. 3 the electron velocities are distributed substantially in accord with Maxwell's Law.[23] Superposed upon this random electron current is the drift current along the axis of the tube towards the anode. In the tube of Fig. 3, the drift current is equal to the arc current I_B.

The ratio of the random current density I_e to the drift current density I_x is a quantity which is of the utmost importance in any analysis of the fundamental nature of gaseous discharges. The fact has been impressed upon us particularly by a study of the anode drop occurring with anodes of various sizes relative to the enclosing tube.

A cylindrical anode 1 cm. in diameter and 3 cm. long in the axis of a tube 3-cm. diameter will reach a dull red heat when it carries about 5 amp. in mercury vapor at a pressure corresponding to 20 deg. C. But if the tube surrounding this anode is made larger or particularly if the anode is placed in a 5-inch bulb placed at the end of the 3-cm. tube, the anode reaches a bright red heat with a smaller current, even less than one ampere. Measurements of the difference of potential between the anode and the space near it, by means of collecting electrodes ($i^2 - \nu$ plots) also prove that the anode drop may assume very large positive values (25 volts or more) if the anode is placed within a large bulb, especially if the pressure of mercury is low.

This phenomenon is readily explained in terms of the relation of the random current to the drift current. Thus let us consider a long cylindrical tube having unit cross-section through which a one-ampere mercury arc passes so that the drift current density is one ampere per unit area. Let us assume that the random current density is two amperes per unit area being thus twice the drift current density.

Consider now a disk-shaped anode having the same diameter as the tube and in a plane perpendicular to the axis of the tube. Let

TABLE XIV

Data obtained with Cylindrical Collectors F, G and D. Tube of Fig. 3.

T_p = 10,000 deg.

1	2	3	4	5	6	7	8	9	10	11	12	13
Run	Bulb Temp. Deg. C.	p_{Hg} Bars	i_B Amp.	E_{BC} Volts	Col-lector	E_{SB} Volts	T_e Deg. K.	I_e ma. cm.$^{-2}$	$n_e \times 10^{-10}$	I_p ma. cm.$^{-2}$	$n_p \times 10^{-10}$	$\frac{d\nu}{dx}$ Volts cm.$^{-1}$
20a	33.0	4.7	4.0	41.0	G	......	.....	......	....	16.0	...	...
20b	35.0	5.5	5.0	39.2	G	......	.....	......	....	23.0	...	...
20c	36.0	5.9	9.0	33.0	G	......	.....	......	....	55.9	...	...
25	15.0	1.0	2.0	39.0	G	− 2.0	30,200	355.0	8.2	0.88	...	...
26	15.0	1.0	0.2	33.5	G	− 1.2	34,700	34.0	0.74	0.073	1.8	...
27	15.0	1.0	0.1	...	G	− 1.8	36,000	16.0	0.34	0.043	1.05	...
28a	32.0	4.3	2.0	39.0	G	− 3.0	23,300	430.0	11.4	1.17	...	...
28b	32.0	4.3	0.2	...	G	− 2.5	22,600	35.0	0.94	....	2.05	...
32	16.0	1.1	4.0	40.1	F	− 5.8	28,000	750.0	18.1	2.1	...	0.24
34	15.5	1.05	0.5	...	F	− 7.9	30,100	121.0	2.8	....	...	...
35a	15.5	1.05	1.0	...	F	− 7.8	32,900	171.0	3.8	0.24	...	...
35b	15.5	1.05	2.0	...	F	− 7.6	26,200	367.0	9.1	0.58	...	...
36a	15.5	1.05	4.0	...	F	− 7.1	25,000	775.0	19.7	2.9	...	...
36b	15.5	1.05	5.9	...	F	− 6.6	22,400	1580.0	42.5	5.5	...	...
37	15.5	1.05	8.0	35.0	F	− 6.1	22,000	1840.0	50.0	....	...	...
44	30.0	3.7	0.1	33.0	F	− 9.0	20,900	......	....	....	...	...
45	30.0	3.7	0.2	36.0	F	−11.0	19,100	14.5	0.4	....	1.6	...
46	30.0	3.7	0.5	40.0	F	− 9.0	24,800	50.0	1.3	....	2.7	...
47	30.0	3.7	1.0	39.0	F	− 9.0	19,000	175.0	5.2	0.4	...	0.32
48a	60.0	33.0	0.2	40.0	F	−17.0	10,600	96.0	3.8	....	...	...
48b	60.0	33.0	0.5	38.2	F	−14.0	9,240	260.0	11.1	....	...	...
49a	60.0	33.0	1.0	38.0	F	−12.0	14,200	480.0	16.3	....	...	0.46
49b	60.0	33.0	2.0	37.0	F	−11.0	14,700	940.0	31.2	....	...	0.53
76	15.0	1.0	i_A2.0	...	D	......	30,000	474.0	11.0	1.7	...	...
79	40.0	8.0	i_A2.0	...	D	......	18,400	490.0	14.5	1.7	...	...
83	60.0	33.0	i_A2.0	...	D	......	12,200	1530.0	55.8	5.0	...	...

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[23] Shottky and J. von Issendorff, *Zeitsch.f.Physik* **26**, 85 (1924), in a recent paper have also found the Maxwellian distribution of electron velocities in a mercury arc. They have measured the heating effect at a negatively charged collector and their results confirm by a very convincing method our conclusion that the currents are due to positive ions and not to electrons emitted.

us assume[24] that the presence of the anode does not materially alter the state of ionization in the gas except within a sheath of relatively small thickness which may cover the anode.

Across any given cross section of the tube there will thus be a current of three amperes of electrons towards the anode (two amperes of random and one of drift) and two amperes of electrons in the opposite direction. Thus the anode, in order to take a current of only one ampere (fixed by the external circuit), must be sufficiently negatively charged with respect to the gas to repel ⅔ of the electrons which are moving towards it. Thus because of the random current there will be a negative anode drop.[25]

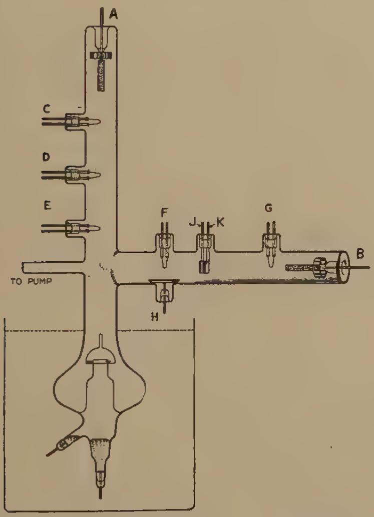

Fig. 3. Mercury Vapor Tube with Various Types of Collectors. (*Repeated from Part II*)

If the area of the disk-shaped anode is reduced until it is only ⅓ of that of the cross-section of the tube, the number of electrons moving spontaneously towards the surface of the anode is just sufficient to carry the current flowing from the anode so that the negative anode drop disappears. If, however, the anode is reduced in size until its area is only 0.1 of the tube cross section, it would only collect 0.3 amp. of electrons if the anode drop were to remain zero. If the anode current is to be maintained at one ampere, the voltage of the circuit must concentrate at the anode until one ampere of electrons are drawn to that electrode.

We have seen,[26] however, that a plane collector at a small positive potential with respect to the ionized gas becomes surrounded by an electron sheath and the electron current which flows is then limited by the rate at which the electrons reach the edge of the sheath, or in other words the current increases with the voltage only in proportion to the surface of the outer edge of the sheath.

Thus if the diameter of the anode is large compared to the thickness of the sheath, the current cannot increase very much even if a positive anode drop does develop. When the anode drop increases sufficiently there is a marked increase in ionization produced by the higher velocity electrons. Since one positive ion neutralizes the space charge of several hundred electrons (because the positive ions remain longer in the sheath) the anode sheath breaks down when one electron out of every few hundred collides with a mercury atom within the sheath. The sheath thickness is nearly independent of the gas pressure so the number of collisions in the sheath is approximately proportional to the pressure. Thus if the anode sheath is 0.05 cm. thick and the free path of the electrons is 20 cm. (at about 3 bars pressure) only one electron out of 400 will collide with an atom in traversing the sheath. As only a fraction of the collisions result in ionization, there would be too few ions produced under these conditions to neutralize the space charge. At higher pressures, or with the thicker sheaths and more efficient ionization that occurs at higher voltages, the positive ions formed decrease the space charge and cause an increase in the sheath thickness which in turn still further increases the ionization. Thus it is that the electron sheath at a plane collector or an anode breaks down suddenly at a certain voltage and the anode drop falls discontinuously to a lower value. Similarly as we decrease the size of an anode in a tube of given diameter, the anode drop first increases and then suddenly the sheath breaks down and the anode drop decreases.

When this breakdown occurs an anode glow appears usually in the form of a sharply defined globular or semispherical region several times more highly luminous than the surrounding region. Within the glow the intensity of ionization is much greater and the conductivity much better than it was before breakdown, but outside of the glow the conditions are much the same as before. Thus the outer surface of the anode glow now becomes the collecting area for the electrons and the extent to which the glow develops depends on the ratio of the random and drift currents.

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[24] This is a useful approximation to the truth. Actually the removal of electrons from the discharge tends to decrease n_e even beyond the edge of the sheath. Furthermore, since the direction of motion of the positive ions is only partly a random motion, there will be a deficiency of positive ions (n_p) outside the sheath. This must tend to reduce also the electron concentration but produces a potential distribution the reverse of the normal gradient in the arc and this in turn brings positive ions towards the anode and partly compensates for the deficiency. These points will be considered in more detail in subsequent publications.

[25] Measurements with collectors confirm the existence of negative anode drops with anodes of large area in proportion to the surrounding tube. The negative drop may become very large if the random current is raised by the injection into the arc of high-speed electrons as from a negatively charged hot cathode.

[26] Part II (Aug., 1924, p. 538).

For example, in the illustration we have considered, the glow which forms over the surface of a collector having 0.1 unit area and carrying one ampere will grow until its boundary is of approximately 0.33 units of area, for this area is required to give the proper anode current with the electron current density of 3 amp. per cm.^{2}

It is clear from this theory that the effect of transferring an anode from a small tube into a large bulb is to decrease the random current density so that a positive anode drop develops and causes abnormal heating of the anode.

Similar phenomena occur when an arc passes through a tube of variable diameter. If the tube gradually decreases in diameter as we pass towards the anode the random current and the drift current densities can both increase in the same proportion so that no discontinuity arises in the potential. But if there is an abrupt decrease in diameter and if the area of the cross section of the smaller tube multiplied by the random current density in the larger tube is less than the drift current in the smaller tube, then it is clear that a potential difference must develop between the two regions sufficient to furnish the ionization needed for building up the random electron current in the smaller tube. To get such a potential difference there must be an electric double layer or double sheath in the gas; negative on the cathode side and positive on the anode side. Experiments show that a sudden decrease in the tube diameter in the direction towards the anode produces a glow with a sharp boundary extending from the smaller out into the larger tube.

C. G. Found with one of the writers has used collectors to study the potential distribution and the intensity of ionization, etc., along the length of a typical glow discharge in nitrogen. The concentration of electrons and ions (n_e and n_p) have relatively very high values in the cathode glow and decrease steadily as we pass through the Faraday dark space until the beginning of the positive column is reached after which no further change occurs. We believe that the Faraday dark space is primarily the result of the abnormally high ratio of the random current to drift current. The high random current allows the drift current to flow with a very low potential gradient. In fact, if the rate of decrease of ionization is sufficiently rapid the high mobility of the electrons causes them to diffuse from the region of high concentration to that of lower concentration near the head of the positive column and thus produces a negative potential gradient throughout the Faraday dark space. The intensity of ionization decreases because of recombination and particularly by the loss of positive ions on the negatively charged walls, and also because of the low rate of production of ions resulting from the small gradient.

In the positive column the potential gradient, because of the lower concentration of electrons, has risen so high that the rate of production of ions just balances the loss by recombination on the walls. In the case of a striated discharge, the number of electrons produced in a striation is more than enough to yield the random current needed to maintain the discharge so that a new dark space appears as the electrons diffuse towards the anode. This subject is being investigated in detail by Karl Compton.

When electrons of 20- to 50-volt velocity are injected into a mercury arc by heating a negatively charged filament (such as E in Fig. 3) the luminosity of the arc is greatly decreased for a length of several centimeters in a direction toward the anode. This artificial production of a Faraday dark space is a direct result of the increase in the electron concentration and random current by the injected electrons. There is also a marked decrease in the voltage drop through the arc. To get these effects it is often sufficient to inject a current of electrons which is only a few per cent of the arc current. These experiments are being continued and promise to throw a great deal of light on the mechanism of the arc.

These phenomena furnish striking proof that the light in the mercury arc is not caused by recombination of ions but is due to the excitation of atoms by electron impacts. The same is true of the positive columns of glow or Geissler discharges in general, although the light produced in the negative glow is probably due in large part to recombination.

In Table XV will be found a summary of the data on the ratio between the random and drift currents. The data in Columns 5, 6, and 7 represent the averages of the values given in Tables XIII and XIV corresponding to the mercury vapor pressures given in Column 3. The drift current density I_x was obtained by dividing the arc current i_B by the area of the cross section of the tube (7.9 cm.^{2}), thus neglecting the fact that the current density near the axis of the tube was greater than near the walls.

The data for collector H contained in Table III[27] were taken simultaneously with those for the corresponding runs recorded in Table XIV. Columns 8, 9, and 10 of Table XV give the average values for collector H calculated from the data of Table III.

A comparison of Columns 6 and 9 shows that the random electron current density I_e was greater near the axis of the tube at collector F, than close to the walls at collector F. The ratio was about 2 to 1 at the lower pressures of mercury and increased up to 4 to 1 at a pressure of 33 bars. It is well known that at much higher pressures (of several centimeters of mercury) arcs in all gases tend to concentrate along a definite arc path, and these experiments indicate that the effect begins gradually at pressures as low as 33 bars. Observation of the arc at this pressure shows that the light intensity is markedly greater along the axis, while at lower pressures it is much more uniform.

The data of Column 6 show that the ratio of random to drift current in a tube decreases at the lower pressures. This is undoubtedly the main cause of the great increase in anode temperature which occurs when the bulb of a mercury arc is cooled below a certain temperature.

A comparison of these data with those of Table XI shows that although the actual value of I_e for a given arc current is much lower when an arc passes into a 5-inch bulb, yet the ratio $\frac{I_e}{I_x}$ is considerably larger. Thus the average values of this ratio from Table XI (5-inch bulb) are

8.2 at a bulb temperature of 0 deg. C.
6.6 at a bulb temperature of 13.4 deg. C.
2.3 at a bulb temperature of 40 deg. C.

The main reason for these high values is probably the presence of the high-speed electrons which came through from the lower bulb (see Fig. 6)[28] and whose effects have been observed and described.[29] The longer electron free path at the lower pressures explains the greater effect at the lower bulb temperatures. With tubes of different design, such as those used in our earlier studies,[30] the ratio I_e/I_x observed in 5-inch bulbs ranged from 1 to 4 according to the position of the collector in the bulb.

When hot cathodes are employed in place of the mercury cathode and the cathode temperature is lowered until the current is limited by the emission of the filament, very high values of I_e/I_x are obtained. Thus the data in Table IV, of the article just referred to, show that I_e/I_x was equal to 40 with an anode voltage of 50 and a pressure of 16 bars.

TABLE XV

Electron Temperatures, Ratio of Random to Drift Current Densities, and Ratio of Electron and Positive Ion Random Currents. Tube of Fig. 3.

1	2	3	4	5	6	7	8	9	10
				CYLINDRICAL COLLECTOR F, C OR D			COLLECTOR H TABLE III		
Source	Bulb Temp. Deg.	Hg Pressure Bars	No. of Obs.	T_e	$\frac{I_e}{I_x}$	$\frac{I_e}{I_p}$	T_e	$\frac{I_e}{I_x}$	$\frac{I_e}{I_p}$
Table XIV	15	1.0	11	28,900	1.60	420	25,000	0.84	382
XIII	16	1.1	9	24,000	1.57	422	.....	...	...
XIV	30	3.7	6	21,600	1.18	400	18,500	0.87	455
XIV	40	8.0	1	18,400	1.94	290	.....	...	...
XIV	60	33.0	5	12,200	4.3	305	8,900	1.04	385

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[27] In referring to Tables, it may be noted that Tables I to VIII appeared in Part II (Aug., 1924, p. 538); and Tables IX to XI in Part III (Sept., 1924, p. 616).

[28] In referring to illustrations, it may be noted that Figs. 1 and 2 appeared in Part I (July, 1924, p. 449); Figs. 3 to 6 in Part II (Aug., 1924, p. 538); and Figs. 7 to 12 in Part III (Sept., 1924, p. 616).

[29] Part III (Sept., 1924, p. 616).

[30] "Positive Ion Currents in the Positive Column of the Mercury Arc," Irving Langmuir, GENERAL ELECTRIC REVIEW, Vol. XXVI, Nov., 1923, p. 733.

Ratio of Electron to Positive Ion Concentrations

The ratio I_e/I_p as shown in Columns 7 and 10 of Table XV has an average value of about 420 and appears to be practically independent of the arc current, but perhaps decreases a little as the pressure of mercury vapor is raised. For equal energies, electrons move 605 times faster than mercury ions, so that if the temperatures T_e and T_p were equal and if I_e/I_p were equal to 605, the concentrations n_e and n_p would be equal. But since the energy put into the arc by the field is delivered first to the electrons, the temperature of the ions T_p must necessarily be lower than that of the electrons. Thus, even if I_e/I_p were 605, the value of n_p would exceed n_e and this difference must be still greater with the lower value of the ratio I_e/I_p given by experiment. Direct determinations of n_p by means of collector currents limited by orbital motion give us the ratio more accurately. Thus the data of Table XIII obtained with the bulb at 16 deg. C. indicate that the ratio n_e/n_p had an average value of 0.45 for a range of arc currents from 0.1 to 8.0 amp. The average of the values from Table XIV is 0.38, and the data of Table XI show that in the 5-inch bulb the ratio decreased from 0.60 to 0.40 as the bulb temperature was raised from 0 to 40 deg. C.

The space charge in any arc, except in the regions of sharp potential gradients (as in the sheaths) must be practically zero, i.e., the total negative charge per unit volume must be very closely equal to the positive charge per unit volume. Any large difference between n_e and n_p must therefore be due to the presence of negative ions. For example, if $n_e/n_p = 0.40$, the number of negative ions must be 0.6 of the number of positives, or there are present 1.5 times as many negative ions per unit volume as electrons. Of course these negative ions would carry only a negligible part of the total current.

Tables III and XIV show that the first run with the tube of Fig. 3 gave positive ion currents about 10 times as great as those obtained later under nearly similar conditions. The second set of runs (Run 24), Table XII, gave currents about three times the normal values. Unfortunately, the electron currents were not measured in these first runs. We believe that these high positive ion currents are due to impurities in the mercury vapor which produce negative ions and thus lead to a corresponding increase in the number of positive ions. Experiments are in progress to measure the effect of electronegative gases on the ratios I_e/I_p and n_e/n_p.

Degree of Ionization of the Mercury Vapor

It is of interest to know what fraction of the mercury atoms in an arc are ionized. The number of ions per cm.^{3} (n_p) increases roughly in proportion to the arc current, but obviously this relation cannot continue to hold if the ionization of the mercury atoms should become complete. Table XVI gives a summary of the data for n_p corresponding to the highest arc currents used and the lowest mercury vapor pressures.

Column 7 gives n_a, the number of mercury atoms per cm.^{3}, calculated on the assumption that the temperature of the mercury atoms corresponds to 1000 deg. K. The last column gives the degree of ionization. With a current density of 0.1 amp. cm.$^{-2}$ in mercury vapor at 1.1 bars the degree of ionization reached 20 per cent. Thus if the current were raised five-fold (to 40 amp. in a 3.2-cm. tube) with the mercury vapor at this pressure the normal current-carrying capacity of the mercury vapor should be reached and a further increase in current could occur only by increasing the velocities of the electrons.

To test out this conclusion and to determine what phenomena occur when the ionization becomes nearly complete, a special tube was constructed in which the arc was made to pass through a quartz "capillary" 24.5 cm. long with an internal diameter of 0.232 cm. The anode and cathode constructions were similar to those of the tube of Fig. 6,[28] and these sections were connected with the intermediate capillary section by tubing 2.5 cm. in diameter. Spherical collectors in this larger tube about 10 cm. from the ends of the capillary were used to measure the space potentials and thus obtain the voltage drop in the capillary. Table XVII gives a summary of the data obtained with this tube.

It was found that when the current was raised to a certain rather sharply defined critical value, the voltage across the tube rose suddenly to several hundred volts and violent electrical surges were produced which causes sparks of several centimeters length to jump across the terminals of a choke coil placed in series with the arc. The inner surface of the capillary then became incandescent. Columns 5 and 6 give the voltage and current observed just before the break occurred. The voltages given in Columns

3 and 5 represent the drop in potential through the capillary tube which was found from the difference in potential between the two spherical collectors by subtracting 6 volts as the estimated drop in potential through the 20 cm. of 2.5-cm. tubing located between the collectors.

At currents below the critical current the tube behaved normally. The potential drop through the capillary *decreased* gradually, usually about 30 per cent in all, as the current was raised from low values (of about 50 or 100 milliamp.) until a minimum potential drop was reached when the current was roughly one-half of the critical current. These minimum potential drops and the corresponding potential gradients are given in Columns 3 and 4. The potential drop rose gradually as the current was raised towards the critical value.

The critical current density (Column 7) is roughly proportional to the square of the pressure of mercury vapor as it is shown by the figures in the last column.

Experiments on this effect are being continued.

TABLE XVI

Degree of Ionization in Mercury Arc

Data from Table	Bulb Temp. Deg.	Pressure Bars	Arc Current Amp.	Current Density I_x Amp. cm.$^{-2}$	$n_p \times 10^{-10}$	$n_a \times 10^{-13}$	n_p/n_a
XI	0	0.23	1.0	0.008	3.0	0.17	0.018
XII	48	14.6	6.0	0.76	340.0	10.6	0.032
XIII	16	1.1	8.1	1.02	162.0	0.80	0.20
XIV	15	1.0	0.2	0.025	1.8	0.73	0.0025

TABLE XVII

Mercury Arc in Quartz Tube. Inside diameter 0.232 cm. Length 24.5 cm.

1	2	3	4	5	6	7	8
Bulb Temp. Deg. C.	Vapor Pressure Bars	Minimum Voltage	Voltage Gradient Volt. cm^{-1}	Critical Volts	Critical Amp.	Current Density Amp. cm^{-2}	Current Density Divided by Square of Pressure
50.0	16.4	42	1.72	>46	>1.65	>39.0	....
40.0	8.0	39	1.60	56	1.58	36.7	0.58
30.0	3.7	34	1.40	58	0.36	8.5	0.62
25.5	2.5	51	2.1	70	0.22	5.22	0.84
20.0	1.53	..	....	180	0.065	1.54	0.66

(To be continued)

ERRATUM

In the article "The First Complete Electrification of an Open-pit Iron-ore Mine in Minnesota," by R. S. Walker, September, 1924, G. E. REVIEW, p. 580, Fig. 17 should have indicated the length of the electric locomotive as 37 ft. 4 in., making the total length of the electric train 133 ft. 4 in. This corresponds with the data given in the appendix on p. 590.

The Sheathed Electrode and An Example of Its Application to the Automatic Welding of Galvanized Tanks

By B. C. Tracey

Merchandise Department, General Electric Company

No longer is electric arc welding thought of only as a tool for making repairs. While in this field it will continue to be more extensively used to reduce the delays and costs chargeable to maintenance, the last few years have witnessed many successful applications of this process to construction and manufacture. Into these broad divisions of industry arc welding has brought its reputation as a saver of time, labor, and material; and accordingly any new applications possess the interest that is attached to improved methods of production.

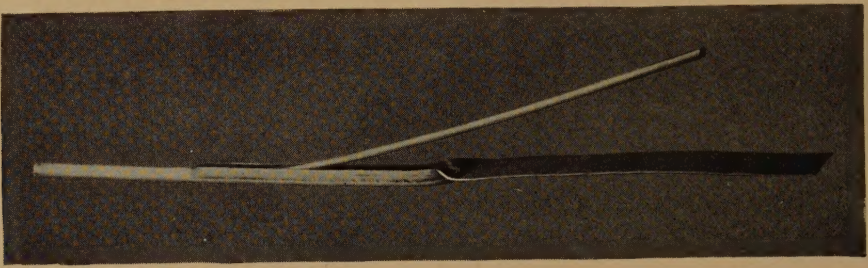

Fig. 1. Sheathed Electrode in Its Construction Stages

As a result of the development of the sheath-wire electrode, the electric arc is replacing the oxy-acetylene torch in an increasing number of manufacturing operations; for example, in welding the seams of underground galvanized gasolene tanks produced at the plant of the Wayne Tank & Pump Company, Fort Wayne, Ind.*

The sheathed electrode is a product of extensive research and differs radically from other electrodes in its make-up and characteristics. It consists of a central metallic core surrounded by a layer of flux which in turn is surrounded by a metallic strip. This unique construction is such that the flux is at all times protected from dissipation and its clean metallic surface renders it adaptable to automatic welding. The outstanding features of the electrode are:

1. Arc stability
2. Ease of manipulation
3. Rapid deposition
4. Good penetration
5. Sound tough welds
6. Economy.

The welding of galvanized iron with the electric arc presents great difficulties, and in many instances it was believed weldable only by the acetylene process. This opinion was held by many until the introduction of the sheathed electrode. In combination with the automatic welding machine great economies can be effected as in the following case of galvanized iron tank production at the Wayne Tank & Pump Company.

By the use of the automatic arc welding machine the welding progresses at the rate of 15 in. per minute or 75 ft. per hour as compared with seven feet per hour when using the oxy-acetylene torch. It is now possible to weld three longitudinal seams of a 550-gal. tank in 35 min. as against the three hours required by the gas process. Furthermore, the over-all manufacturing time per tank has been reduced from seven hours to five hours. In addition to the time saved, another favorable feature of the use of the sheathed electrode is that the galvanizing on the inside of the tank adjacent to the weld is retained in good condition, whereas, by using the oxy-acetylene process, approximately one inch of the galvanizing was burned away from the sides of the weld on both the inside and outside of the tank.

These tanks are made of ⅛-in. galvanized sheet iron and have three seams 120 deg. apart and each 116 in. long. The circumference of the tank is 118 in. The stage of the process in which the greatest economy has been achieved is in the uniting of these longitudinal seams where full advantage is taken of electric welding by employing the sheathed electrode and the automatic electric arc welding machine. This machine, illustrated in Fig. 2, consists of a framework for holding the tank in position and for carrying the automatic welding head and the reel of sheath-electrode wire. The joint to be welded is placed between two clamping bars and a backing-up bar. Along this seam travels the automatic welding head which feeds the electrode wire to the arc.

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*The volume of this production is shown by the photograph appearing on page 22 of the advertising section.

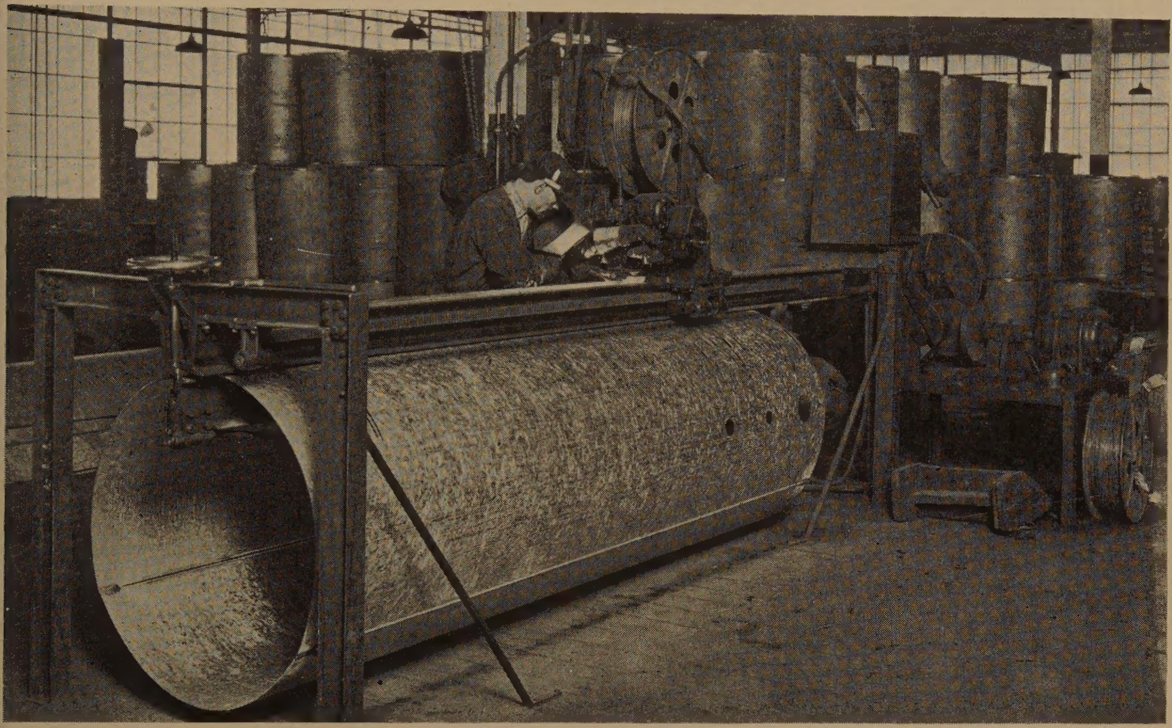

Fig. 2. Welding Longitudinal Seams of No. 12 Gauge Galvanized Iron Tanks Using Automatic Arc Welder and the Sheathed Electrode

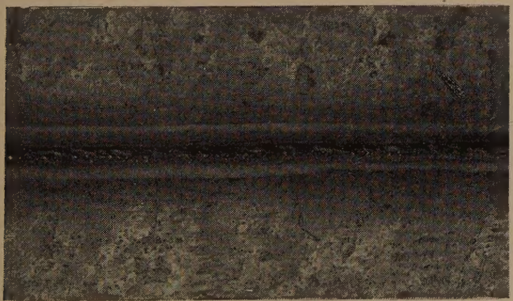

Fig. 3. Close-up of a Section of Galvanized Iron Tank Weld as Shown in Fig. 2

The initial operation of welding consists in tacking each of the longitudinal seams at both ends, the tack weld being approximately three inches long. Before tacking, the plates are placed about ⅛ in. apart, but they draw up tight when the tack is completed. The tank thus formed is placed on the automatic welding machine, Fig. 2, and the arc struck at one end and allowed to continue without breaking to the other end. The clamps are then released and the tank rotated through 120 deg. to the next seam. The automatic head is then made to travel in the opposite direction on the second seam. This operation is again repeated for the third seam.

The savings effected by electric arc welding paid for the installation of the first machine in two months' operation.

LIBRARY SECTION

Condensed references to some of the more important articles in the technical press, as selected by the G-E Main Library, will be listed in this section each month. New books of interest to the industry will also be listed. In special cases, where copy of an article is wanted which cannot be obtained through regular channels or local libraries, we will suggest other sources on application.

Charts

Engineering Conversion Chart. Swain, P. W.
Power, Sept. 9, 1924; v. 60, p. 413.
(Presents a chart for converting quantities from one engineering unit to another, such as atmospheres to pounds per square inch, etc.)

Electric Controllers

Latest Improvements in Locomotive Control. Johnson, H. H.
Coal Age, Sept. 11, 1924; v. 26, pp. 367-370.
(On controllers for mine locomotives.)

Electric Drive—Steel Mills

Electricity's Contribution to the Steel Industry. Pauly, K. A.
A. I. E. E. Jour., Sept., 1924; v. 43, pp. 831-839.

Electrifying Ten-Inch Merchant Mill. Wohlgemuth, M. J. and Morgan, Jr., M. H.
Elec. Wld., Sept. 6, 1924; v. 84, pp. 465-468.
(Illustrates and describes electric drive equipment in the McKeesport works of the Firth-Sterling Steel Company.)

Electrical Machinery—Altitude Effects

Altitude Correction for Temperature Rise.
Elec. Wld., Aug. 30, 1924; v. 84, pp. 420-421.

Temperature Rise of Stationary Electrical Apparatus as Influenced by Radiation, Convection and Altitude. Montsinger, V. M. and Cooney, W. H.
A. I. E. E. Jour., Sept., 1924; v. 43, pp. 803-812.

Elevators, Electric

Operation of Electric Elevator Machines—General Principles. Annett, F. A.
Power, Sept. 9, 1924; v. 60, pp. 414-416.

Locomotives, Oil-Electric

Oil-Electric Locomotive Built for Switching Service.
Engng. News-Rec., Sept. 4, 1924; v. 93, pp. 390-391.
(Illustrated description of the locomotive built jointly by Ingersoll-Rand and G-E for the N. Y. C. R. R.)

Measuring Instruments

Electrical Frequency Analyzer. Wegel, R. L. and Moore, C. R.
A. I. E. E. Jour., Sept., 1924; v. 43, pp. 798-802.
(Describes a device for recording the frequency and magnitude of each component of a complex a-c.)

Pipe Joints

Pipe Joints for High Pressures and Temperatures.
Power, Sept. 9, 1924; v. 60, pp. 396-397.

Radio Stations

Where the Radio "Calls" Come From. Powell, Elbridge S.
Elec. Rec., Sept., 1924; v. 36, pp. 156-157.
(Explains how the radio station call letters are assigned throughout the world, particularly in the U. S. Lists the blocks of letters assigned to the various countries.)

Radiodynamics

First Radio-controlled Substation.
Elec. Wld., Sept. 6, 1924; v. 84, p. 479.
(Brief, general account of the Northern Indiana Power Company's radio-operated substation at Tipton, Indiana.)

Steam Turbines—Lubrication

Improving the Lubrication System of Steam Turbines. Brown, Claude C.
Power, Sept. 9, 1924; v. 60, pp. 420-422.

Steel, Alloy

Stainless Steel and Stainless Iron. Parmiter, O. K.
Am. Soc. St. Treat. Trans., Sept., 1924; v. 6, pp. 315-340.
(Treats of history, manufacture, composition, working, and uses.)

Substations

Portable Substation with Telescopic Tower.
Elec. Rwy. Jour., Aug. 30, 1924; v. 64, pp. 309-310.
(Illustrates and describes a railway substation mounted on a railway car, as used by the Interstate Public Service Company.)

NEW BOOKS

Alignment Charts for Engineers and Students. W. J. Kearton and George Wood. 220 pp., 1924. Phila., J. B. Lippincott Co.

Arc Welding Handbook. C. J. Holslag. 250 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.

Electrical Measuring Instruments and Supply Meters. D. J. Bolton, 328 pp., 1924, N. Y., E. P. Dutton & Co.

Elements of Electrical Design. Alfred Still. 535 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.

Manual of Engineering Drawing. Ed. 3, rev. & enl. Thomas E. French. 409 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.

Shop Mechanics. Pt. I: Shop Arithmetic. Ed. 2. Earle B. Norris and K. G. Smith. 257 pp., 1924, N. Y., McGraw-Hill Book Co., Inc.